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# USAAVLABS TECHNICAL REPORT 70-44

# INVESTIGATION OF FEASIBILITY OF INTEGRAL GAS TURBINE ENGINE SOLID PARTICLE INLET SEPARATORS

## PHASE I, FEASIBILITY STUDY AND DESIGN

By

William J. McAnally, III
Max T. Schilling

August 1970

U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA
CONTRACT DAAJ02-70-C-0003
PRATT & WHITNEY AIRCRAFT DIVISION
UNITED AIRCRAFT CORPORATION
FLORIDA RESEARCH AND DEVELOPMENT CENTER
WEST PALM BEACH, FLORIDA



U. S. ARMY MATERIEL COMMAND



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The objectives of this contractual effort were to study the feasibility of solid particle inlet separator concepts functioning as integral parts of aircraft gas turbine engines, select the two most promising concepts, and test models of the selected concepts.

This report was prepared by Pratt & Whitney Aircraft Division of United Aircraft Corporation under the terms of Contract DAAJ02-70-C-0003. It describes the feasibility study and concept selection phase of the overall effort.

The concepts selected will be modeled and tested. The test results will be presented in a subsequent report.

This report has been reviewed by technical personnel of this Command, and the conclusion contained herein is concurred in by this Command. The U. S. Army Project Engineer for this effort was Mr. Robert A. Langworthy.

Task 1G162203D14417
Contract DAAJ02-70-C-0003
USAAVLABS Technical Report 70-44
August 1970

# INVESTIGATION OF FEASIBILITY OF INTEGRAL GAS TURBINE ENGINE SOLID PARTICLE INLET SEPARATORS

Final Report

Phase I, Feasibility Study and Design

By

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Prepared By

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## SUMMARY

Helicopter operations from unimproved landing sites have demonstrated the vulnerability of unprotected gas turbine engines to sand and dust ingestion. As an interim solution, engine inlet filtration or particle separator devices have been added to engines and aircraft that were already designed and developed. However, there is a need for particle separators designed to be integral with the engine from its conception to minimize penalties in engine performance, weight, maintainability, and reliability. The objective of this program is to conduct a two-phase investigation of particle separators intended to be an integral part of future advanced-technology gas turbine engines. Phase I involves feasibility study and design; Phase II involves feasibility demonstration. The effort reported herein describes the work accomplished during the first phase. Eight particle separator concepts were determined to be feasible, and preliminary design study layout drawings were prepared for each. Design information for three of the concepts was obtained from organizations that have been active in the field of particle separation; a review of current separator designs led to the development of a new concept; and the rest were formulated by Pratt & Whitney Aircraft. The eight separator concepts were evaluated with respect to each other for each of ten rating factors. The two most promising concepts, "semi-reverse flow" and "powered mixed-flow," were selected for feasibility demonstration. Test hardware was then designed to experimentally evaluate the two selected concepts.

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## LIST OF SYMBOLS

| | |
|---|---|
| $A$ | Particle area (frontal area of sphere), $ft^2$ |
| $C_D$ | Particle drag coefficient |
| $d$ | Particle diameter, microns (in. x $10^{-6}$) |
| $D_T$ | Tip diameter, in. |
| $E$ | Field strength, volts/meter |
| $F_{drag}$ | Particle drag force, lb |
| $F_{elec}$ | Electrostatic force, newtons |
| $N$ | Impeller rotational speed, rpm |
| $P$ | Pressure, in. $H_2O$ |
| $Q$ | Particle charge, coulombs |
| Rey | Reynolds number |
| $u_n$ | Velocity normal to potential flow streamline, fps |
| $u_s$ | Streamline velocity, fps |
| $V$ | Velocity, fps |
| $W$ | Mass flow, $lb_m$/sec |
| $\beta$ | Gas or particle swirl angle, deg |
| $\theta$ | Impeller inlet total temperature correction factor = $T_T/519.6$ |
| $\delta$ | Impeller inlet total pressure correction factor = $P_T/2116$ |
| $\rho$ | Density, $lb_m/ft^3$ |
| $\mu$ | Microns, in. x $10^{-6}$ |

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## INTRODUCTION

Because gas turbine engines require high airflow per horsepower, they have always been vulnerable to degradation caused by erosive particle contaminants in the air. When subjected to such contamination, degradation is evidenced by loss of power, loss of surge margin, and attendant increased specific fuel consumption due to either erosion or fouling of precision airfoil sections in the compressor and turbine. The majority of early gas-turbine-engine experience was obtained with fixed-wing aircraft operating from paved runways, and particle ingestion was not a significant problem under those conditions. However, recent tactical helicopter operations from unimproved landing sites have forced a reappraisal of the vulnerability of gas turbines to solid-particle ingestion. Figure 1 shows Pratt & Whitney Aircraft gas turbines powering a Sikorsky Aircraft CH-54 Tarhe helicopter under these adverse operating conditions. Premature engine removals due to resultant erosion damage have drastically reduced the time between overhaul (TBO), in some cases by a factor of 10 or more. Generally, when the engines were overhauled, all compressor components had to be replaced. As a result, virtually all helicopters now operating in Southeast Asia have some form of protection against sand and dust erosion.

Two approaches to solving the problem were apparent: either remove the particles from the airstream, or make the engines more erosion resistant. Because the need was urgent and the particle-removal approach was best suited to quick implementation, this was the course adopted by both engine and airframe manufacturers for an interim solution. Particle removal was accomplished by several differing concepts of both barrier filters and inertial devices.

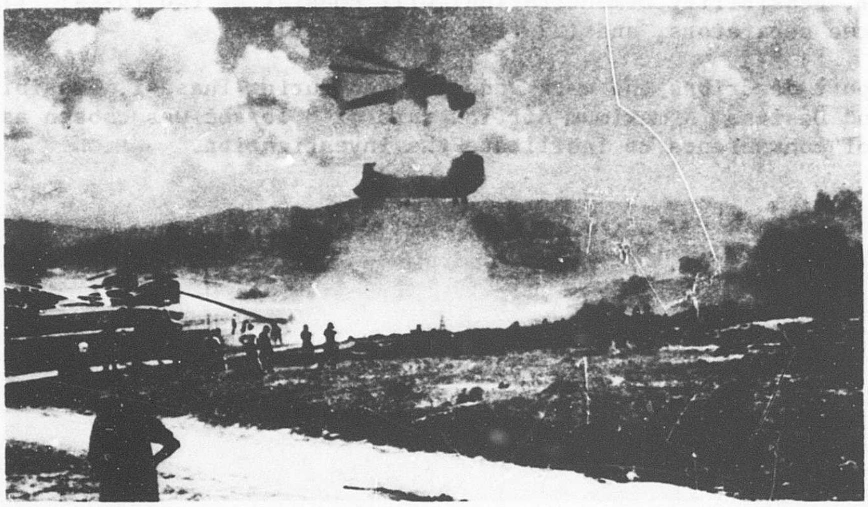


Figure 1. Helicopters Operating From Unimproved Landing Sites.

The engine inlet filtration devices now in use have all been developed as "field fixes;" i.e., they were added as an afterthought to an already designed and developed engine and aircraft. There have been few recent improvements in the state-of-the-art of engine inlet protection devices. Basically, most manufacturers have taken filtration concepts used for years in the industrial gas handling field and have modified them to meet the more stringent volume and weight limitations imposed by flight-type hardware. However, both the static-type filters and the inertial separators produced thus far suffer from some serious drawbacks, such as reduced engine performance, increased aircraft weight, maintenance requirements, lack of anti-icing, and FOD problems attributed to the separator itself. At the same time, field tests, as well as new gas turbine developments, are creating increasingly stringent requirements for greater engine protection, higher efficiency, and smaller package size for a given airflow. An engine inlet particle separator that is designed as an integral part of the engine may offer advantages or reduced penalties in engine performance, weight, maintainability, and reliability, as well as making the separator design invariant with aircraft installation. As a result, there is a need to investigate separators designed to be integral with the engine from its conception, to determine if the above penalties can be minimized and if the conflicting requirements of minimum volume, high efficiency, and low pressure drop can be satisfied.

The objective of this program is to conduct an analytical and experimental investigation of the feasibility of particle separators intended to be an integral part of the inlet of future advanced-technology gas turbine engines. The 12-month program is being conducted in two phases. Phase I, Feasibility Study and Design, will consist of four tasks: (1) review current separators, (2) determine feasibility of new concepts, (3) select two concepts for testing, and (4) prepare manufacturing drawings. Phase II, Feasibility Demonstration, will consist of two tasks: (1) fabricate two separators, and (2) test two separators.

This report describes the work accomplished during Phase I, Feasibility Study and Design. A maximum airflow rate of 8 lb/sec was chosen as a matter of convenience to facilitate the investigation.

## TASK 1 - CURRENT SEPARATOR REVIEW

In this task, existing aircraft gas turbine engine inlet particle separator designs were reviewed to determine the feasibility of adapting these designs to an inlet separator integral with the basic engine. Of the separators currently available, multiple-element vortex-tube separators are in the widest use. Because Sikorsky Aircraft engineers have successfully developed and installed vortex-tube separators on their CH-53 and CH-54 helicopters, they were retained as consultants for this type of separator.

### SIKORSKY AIRCRAFT VORTEX-TUBE STUDY

Sikorsky conducted a performance trade-off study comparing various vortex-tube elements of different diameters and lengths. They prepared a relationship (Figure 2) for approach velocity versus element pressure drop and approach area that compares various vortex elements, and the Wright-Patterson Aerospace Research Labs (ARL) semi-reverse-flow swirl chambers. The most favorable pressure drop/approach area relationship is shown by curves 2 and 3 of Figure 2. Installed separation efficiency and scavenge flow requirements for the above vortex elements are listed in Table I. The ARL swirl chambers offer the most favorable efficiency and scavenge flow characteristics, but at the expense of approach area, as shown in Figure 2.

TABLE I. VORTEX-ELEMENT CHARACTERISTICS

| Vortex Element | Dia. x Length (in.) | Installed Efficiency AC Coarse at 4 in. $H_2O$ $\Delta P$ (%) | Scavenge Flow (%) |
|---|---|---|---|
| ARL Swirl Chamber | 1.88 x 4.75 | 95 | 2.5 |
| Vortex Tube A | 0.75 x 2.8 | 91 | 8 |
| Vortex Tube B | 1.0 x 2.75 | 90 | 10 |
| Vortex Tube C | 1.0 x 3.75 | 92 | 10 |
| Vortex Tube D | 1.5 x 4.0 | 88 | 10 |
| Vortex Tube E | 1.5 x 6.0 | 93 | 10 |

The data presented in Figure 2 and Table I were obtained from manufacturers' brochures and Reference 1, except for the information of the ARL swirl chambers which was obtained from Reference 2.

### OTHER AIRCRAFT GAS TURBINE SEPARATORS

A brief literature review of current engine inlet particle separator designs was conducted. The United Aircraft of Canada, Ltd. (UACL), Lycoming, and Boeing-Vertol inertial separators and the General Electric Co. (GE) swirl separator were determined to be of interest. A summary of the characteristics and performance of the separators is given in Table II.

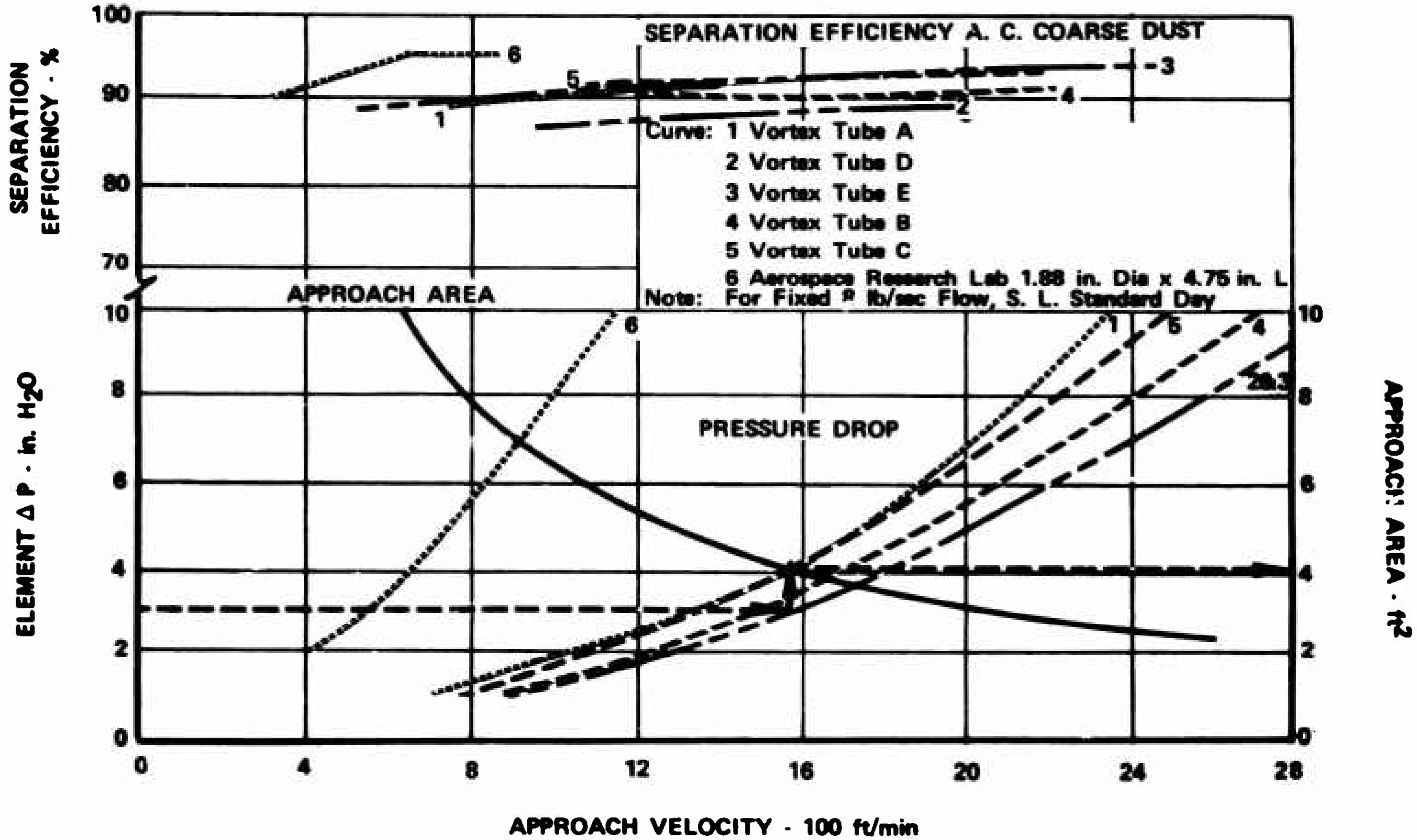



Figure 2. Vortex-Tube Performance Comparison.

TABLE II. SUMMARY OF SEPARATOR CHARACTERISTICS

| Model | Efficiency AC Coarse (%) | Scavenge Flow (%) | Pressure Drop (in. $H_2O$) | Reference |
|---|---|---|---|---|
| UACL | 70 | 29 | * | 3 |
| Lycoming | 38 | 10 | 6.5 | 4 |
| G.E. | 70 | 10 | 10.8 | 1 |
| Boeing | 85 | 10 | 3.2 | 5 |

*Part of turboprop engine inlet.

The UACL inertial separator is part of the U21A turboprop intake system. It was originally designed for anti-icing purposes and depends on ram air derived from forward motion for operation.

The Lycoming inertial separator is a radial-inflow bellmouth assembly cantilevered from the engine inlet housing. It was developed as a field-installed kit for the T53 engine installed in the Bell UH-1 helicopters.

The Boeing-Vertol particle separator is an inertial type designed to fit the CH-46 helicopter. It uses a bellmouth inlet to focus the dust particles in such a manner that they are captured by a scavenge duct located in the center of the inlet. Engine airflow passes around the OD of the centrally located scavenge duct.

The General Electric particle separator is an axial-flow cyclone type designed to attach directly to a T58 engine. It has 19 inlet swirl vanes attached to an extension of the engine bullet nose, a scavenge scroll located around the OD of the separator, and 26 exit deswirl vanes to straighten the airflow into the engine.

## TASK 2 - CONCEPT FEASIBILITY STUDIES

In this task, new or innovative integral engine inlet particle separator concepts were formulated and evaluated to determine feasibility. A computer program that can plot trajectories of various-size particles was developed for use as an analytical design tool to aid in determining the particle concentrating effectiveness of various separation concepts and duct contours. Eight preliminary design study layout drawings were prepared for the concepts that evolved. The drawings are conceptual in nature, as opposed to detail designs for a specific engine, but contain sufficient information to assist in evaluating the various concepts. Of the eight separator concepts determined to be feasible, three are based on design information obtained from organizations that have been active in the field of particle separation, one is a new concept developed as a result of the review of current separator designs in Task 1, and the remainder were formulated by Pratt & Whitney Aircraft.

### COMPUTER PARTICLE TRAJECTORY ANALYSIS

The particle trajectory computer program was developed and used as an analytical design tool to aid in determining the effectiveness of various separation concepts and duct contours in concentrating particles. The analysis utilizes two computer programs to formulate particle trajectory plots, as illustrated in Figure 3. The coordinates of the duct contour are first input into a program that provides duct flow properties based on numerical solutions of equations for incompressible turbulent swirling flow through axisymmetric annular ducts. The duct contour, flow field, and particle data are then input into a trajectory calculation program which computes and plots the trajectories of particles as they move through the duct. Details of these calculations, which balance the centrifugal and drag forces on a particle, are presented in the appendix.

This analysis offers advantages not included in many analytical approaches. It is able to analyze axisymmetric annular ducts, swirling flow and swirling particles, and it incorporates turbulent boundary-layer calculations which provide aerodynamic flow separation data. Other analyses, such as electric analog potential flow field mapping, are limited to nonswirling two-dimensional ducts and provide no indication of flow separation.

Since no test data were available with which to verify the computer particle trajectory calculations, an attempt was made to correlate the trajectory calculations with Russian data presented in Reference 6. A theoretical simulation was made of various particle trajectories in a blade cascade, with the resulting comparison presented in Figure 4 . It is seen that the P&WA calculations predict greater deflection for the smaller particles. However, the P&WA calculated trajectory results provide better agreement with the test data from Reference 6, in which erosion patterns indicate greater particle deflections than the Russian calculations had predicted.

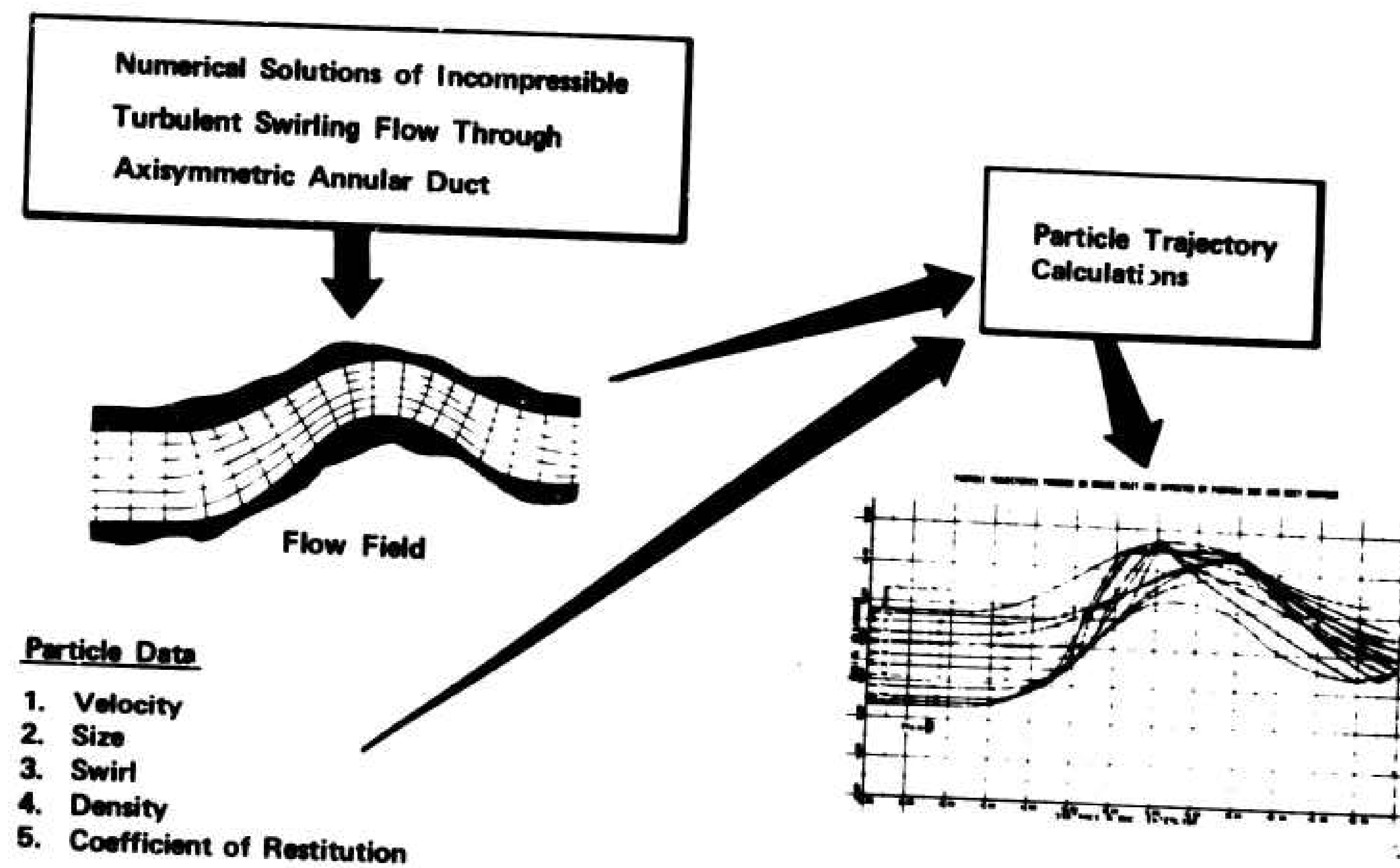



Figure 3. Computer Particle Trajectory Analysis.

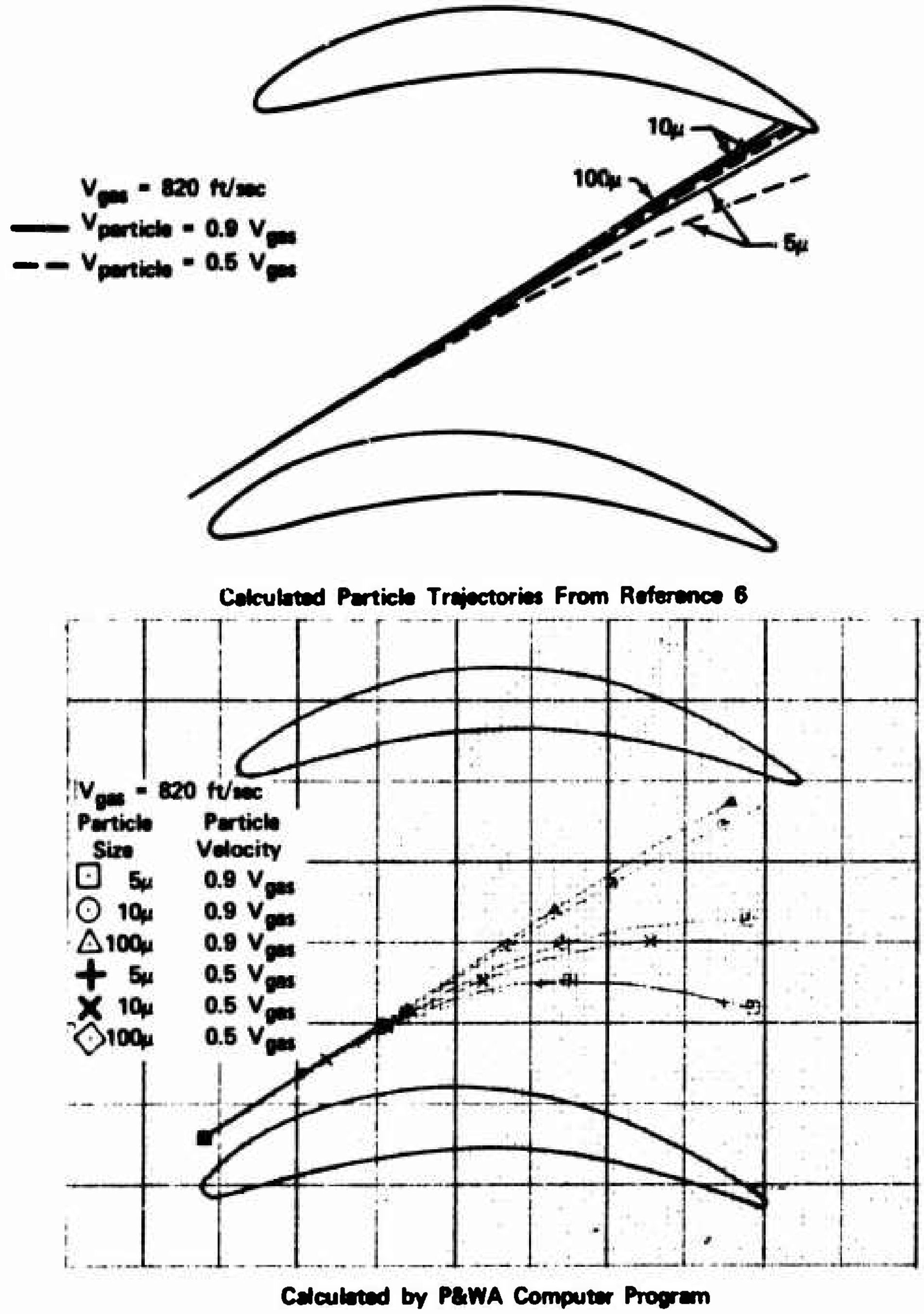



Figure 4. Comparison of Particle Trajectories in a Cascade.

The particle trajectory computer program has the capability of plotting three views of the particle paths through the duct, as shown on Figure 5. The first and standard plot is the radial-axial view, in which axial (z) positions are undistorted but all radial positions are rotated back to the y-z plane. The true axial view (i.e., x-y plane) and true side view (i.e.,y-z plane) are plotted when analyzing ducts incorporating swirling flow, as these views illustrate circumferential variations in the particle trajectories. The gas swirl angle is the angle (B) the velocity vector makes with the y-z plane. In using the computer program to study the various separator concepts, ground rules were established to maintain a degree of commonality:

a) duct inlet velocities were calculated on the basis of a flow rate of 8.0 lb/sec, except for the semi-reverse flow concept which was based on 11.2 lb/sec to provide for a 40% scavenge flow

b) gas inlet total pressure equal to 14.7 $lb/in.^2$

c) gas inlet total temperature equal to 59°F

d) particle density of 165 $lb/ft^3$

e) particle coefficient of restitution of 0.75

f) particle velocity at inlet equal to 0.9 gas inlet velocity

## PRELIMINARY CONCEPT DESIGN 1 - SELF-CLEANING BARRIER FILTER

A self-cleaning barrier filter design was of interest because of the high separation efficiency that can be obtained with a barrier filter. Although barrier filters have been used for engine protection, they require a high degree of maintenance, are prone to clogging, and cannot be anti-iced.

The design approach that was taken for integrating a barrier filter with the engine was to minimize the additional volume that would be required. A reduced-scale preliminary design sketch is presented as Figure 6 . For this concept, a cylindrical filter is wrapped around the OD of an engine and is automatically back-flushed when a preset pressure drop across the filter is reached. By wrapping the filter around the engine, not only is the added volume minimized, but some noise suppression and engine protection are also realized.

A visit was made to Southwest Research Institute (SRI), San Antonio, to discuss the use of barrier filters. Design information was obtained for back-flushed barrier filter design which was based on a program SRI conducted for the Army Engineer Research and Development Labs (Reference 7).

During this program it was determined that by using a chopped, high-frequency, high-pressure back-flush, which would vibrate the barrier filter material

at its natural frequency, the filter element could be thoroughly cleaned without an increase in the cleaned pressure drop. With other filter-cleaning techniques, the cleaned pressure drop tends to increase continuously. However, with this vibratory cleaning process the filter media began to break down (regardless of material) after about 25-30 cleanings. The prototype filter was 35 inches in diameter by 9 inches long and exceeded 98% separation efficiency using AC fine dust with a 4- to 6-inch $H_2O$ pressure drop at 5.23 lb/sec. Some concern was expressed about cleaning the filter if the pleats were too closely packed; hence, a relatively coarse pleating of 25 per foot was used.

Due to space limitations, the SRI filter operated at a filter media (i.e., airflow) velocity of 73 ft/min. However, a practical maximum velocity of approximately 60 ft/min was recommended to minimize particle migration. Interestingly, all particle sizes had been found to migrate through barrier filters. The filter in the P&WA concept was conservatively sized for 30 ft/min filter media velocity, since, by wrapping it around the OD of an engine, sufficient surface area was readily available. Based on SRI test data, it was estimated that the P&WA filter design could hold approximately 350 grams of dust prior to being back-flushed. It was estimated that compressor bleed air usage required for back-flushing the filter and operating the drive mechanism would result in approximately a 3% power loss during the cleaning cycle. Should the filter tend to become clogged due to encountering icing conditions or in-flight rain, air pressure recovery can also be provided by a bypass system that has been provided in the concept. A toroidal diverter is used to change the airflow from the filter to a ram inlet duct. Anti-icing capability for the support struts could be provided should it be required. The toroidal diverter is actuated by an annular piston mechanism. Normally, it would be spring loaded in the ram inlet position for fail-safe purposes. High-pressure air from the compressor is used to load the annular piston and hold the toroidal diverter in the filter position. There would be no performance loss after the toroidal diverter was actuated to the separator position because no continuous flow of high-pressure air from the compressor would be required.

## PRELIMINARY CONCEPT DESIGN 2 - ELECTROSTATIC SEPARATOR

Electrostatic precipitators were of interest for protecting an aircraft gas turbine engine because of the precipitator's potential low pressure drop and ability to separate small particles. Although electrostatic precipitators have generally been excluded because of their large size and high-voltage requirements, two considerations warranted evaluating this concept as an integral separator. The first consideration was the recent development of high-power piezoelectric crystals that could be utilized to provide a very compact high-voltage power package. The second consideration was the idea of electrostatically diverting the dust particles into a region of concentration and then bleeding scavenge air from that region. This is in contrast to the conventional practice of electrostatically precipitating the particles on a charged plate and then periodically vibrating or washing the plate to dislodge the accumulation of particles.

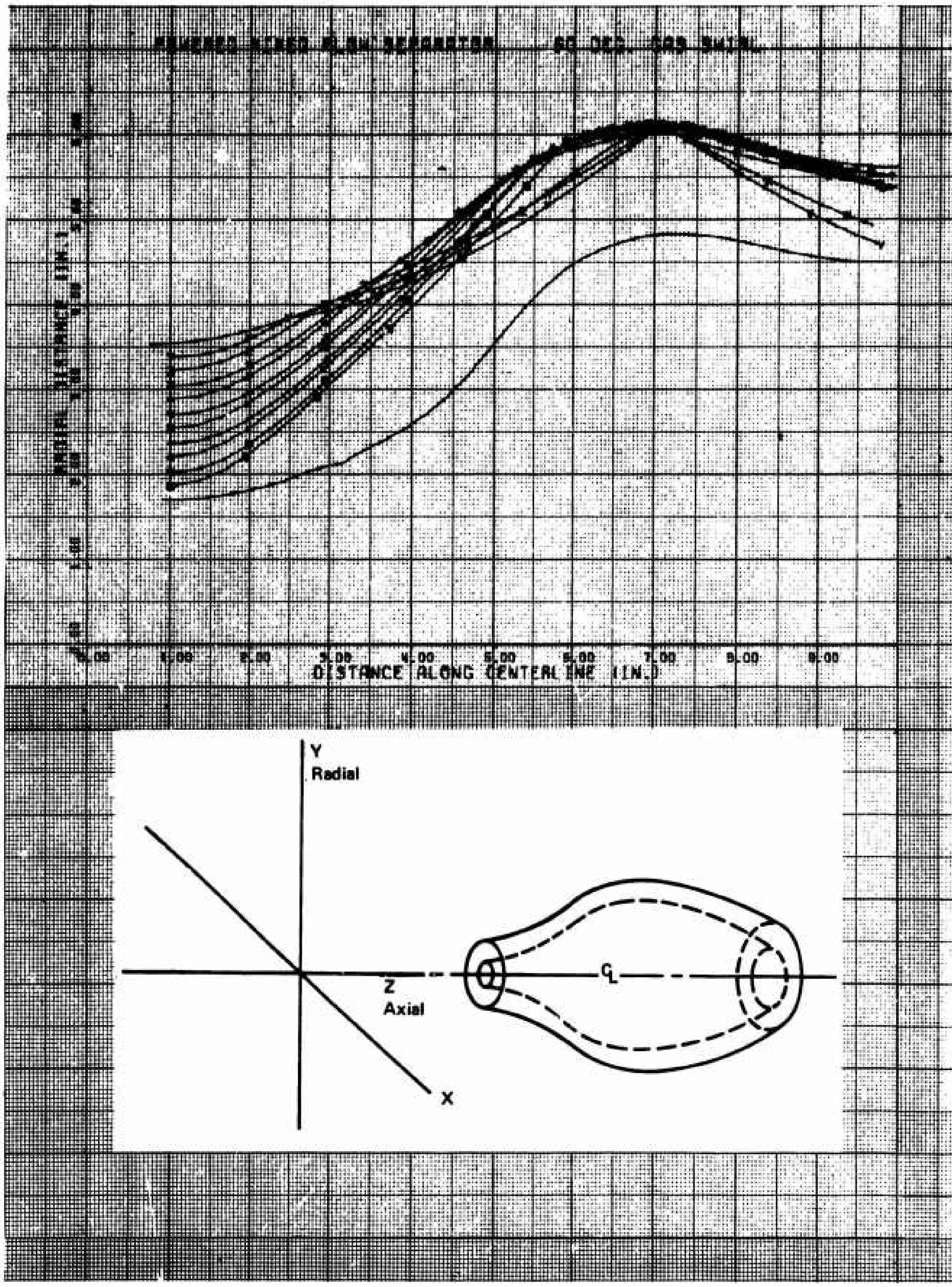



Figure 5. Plotted Output From Computer Particle Trajectory Calculations.

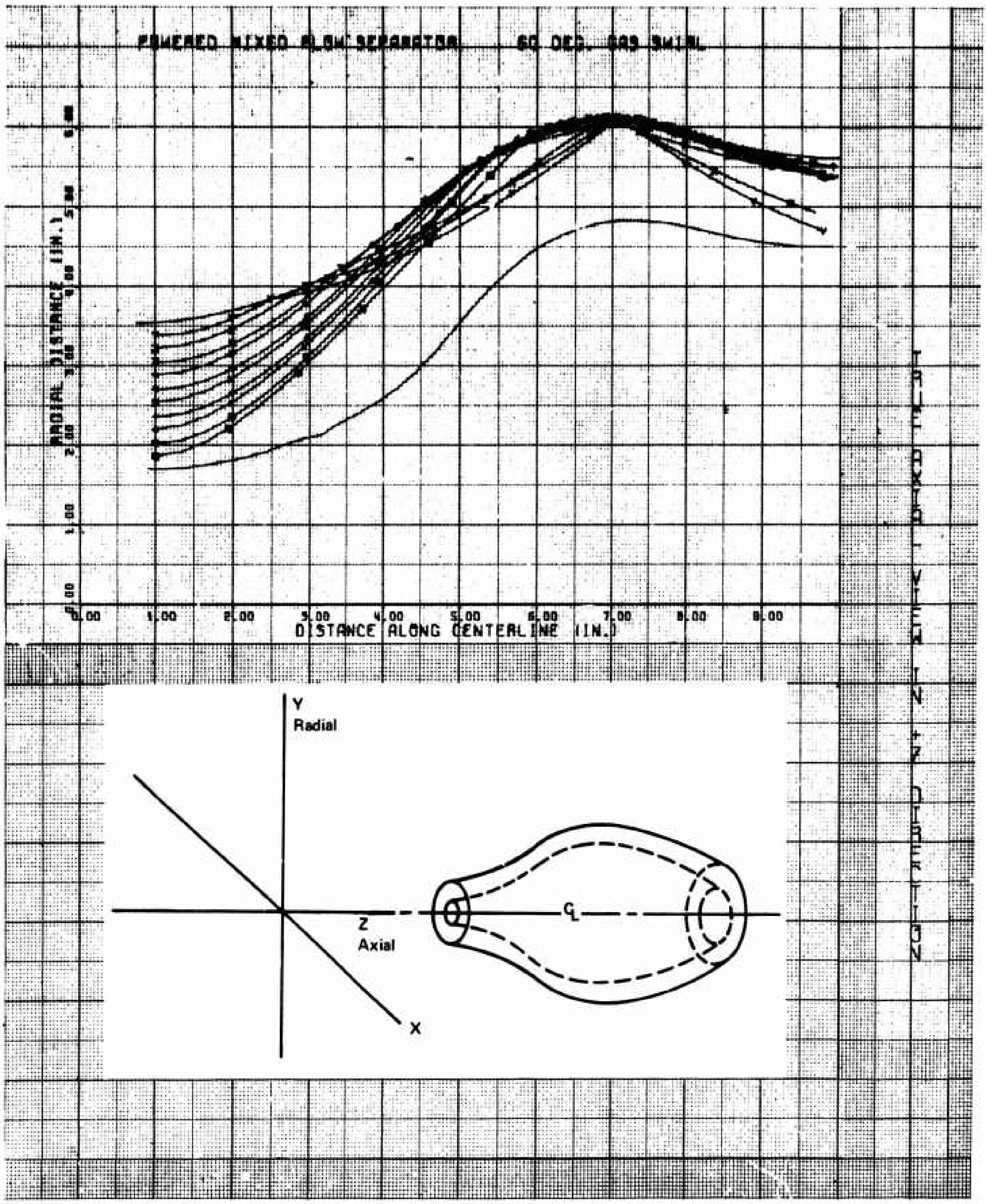
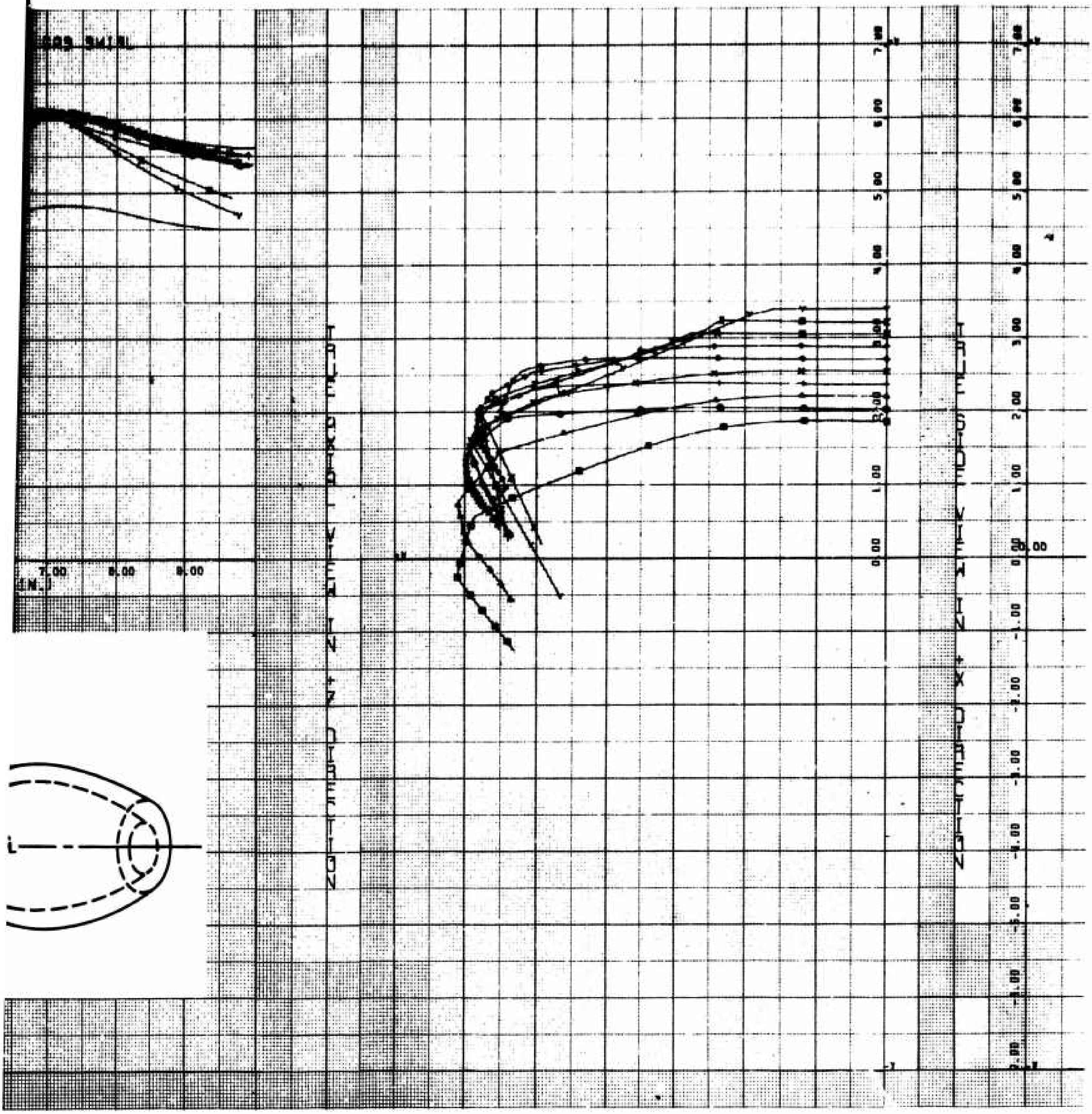



Figure 5. Plotted Output From Computer Particle Trajectory Calculations.

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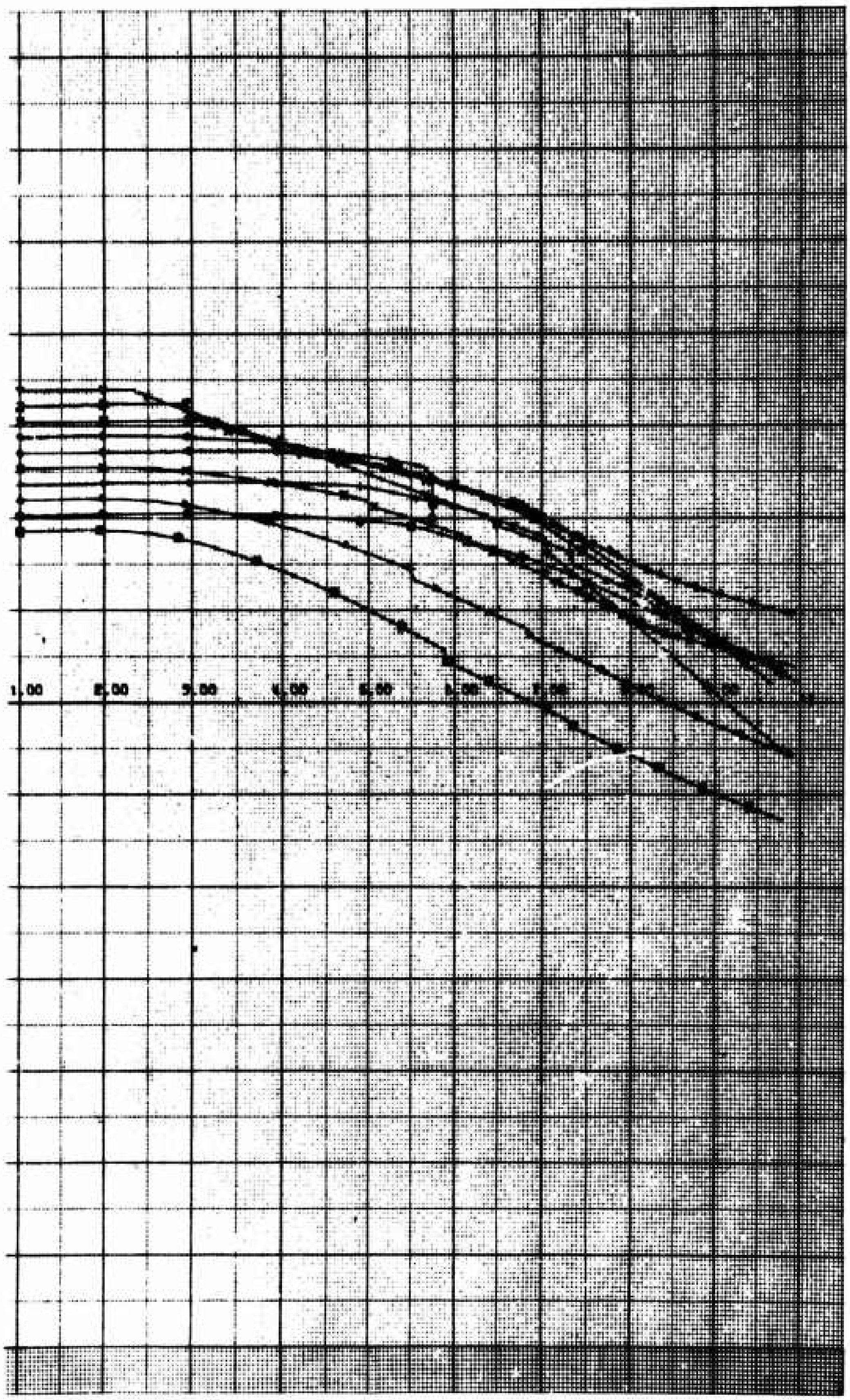
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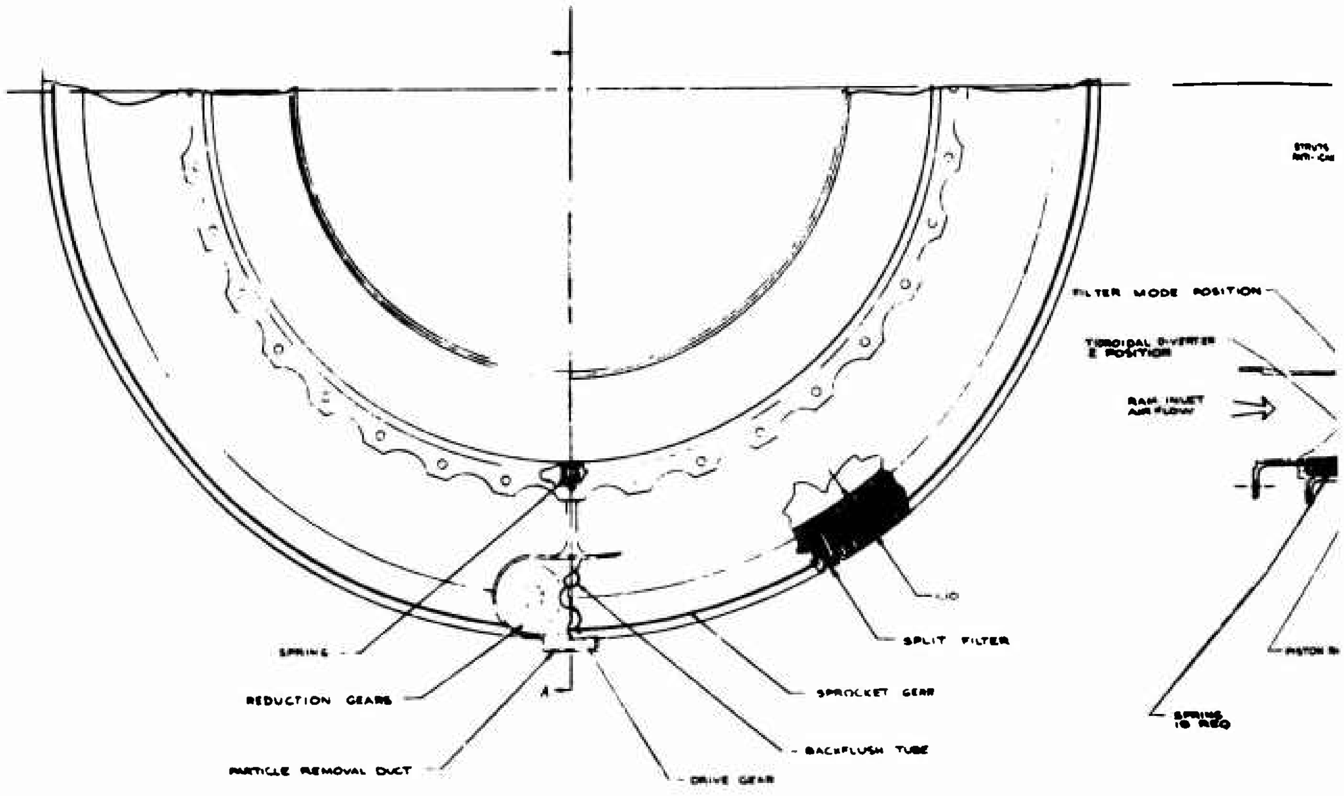
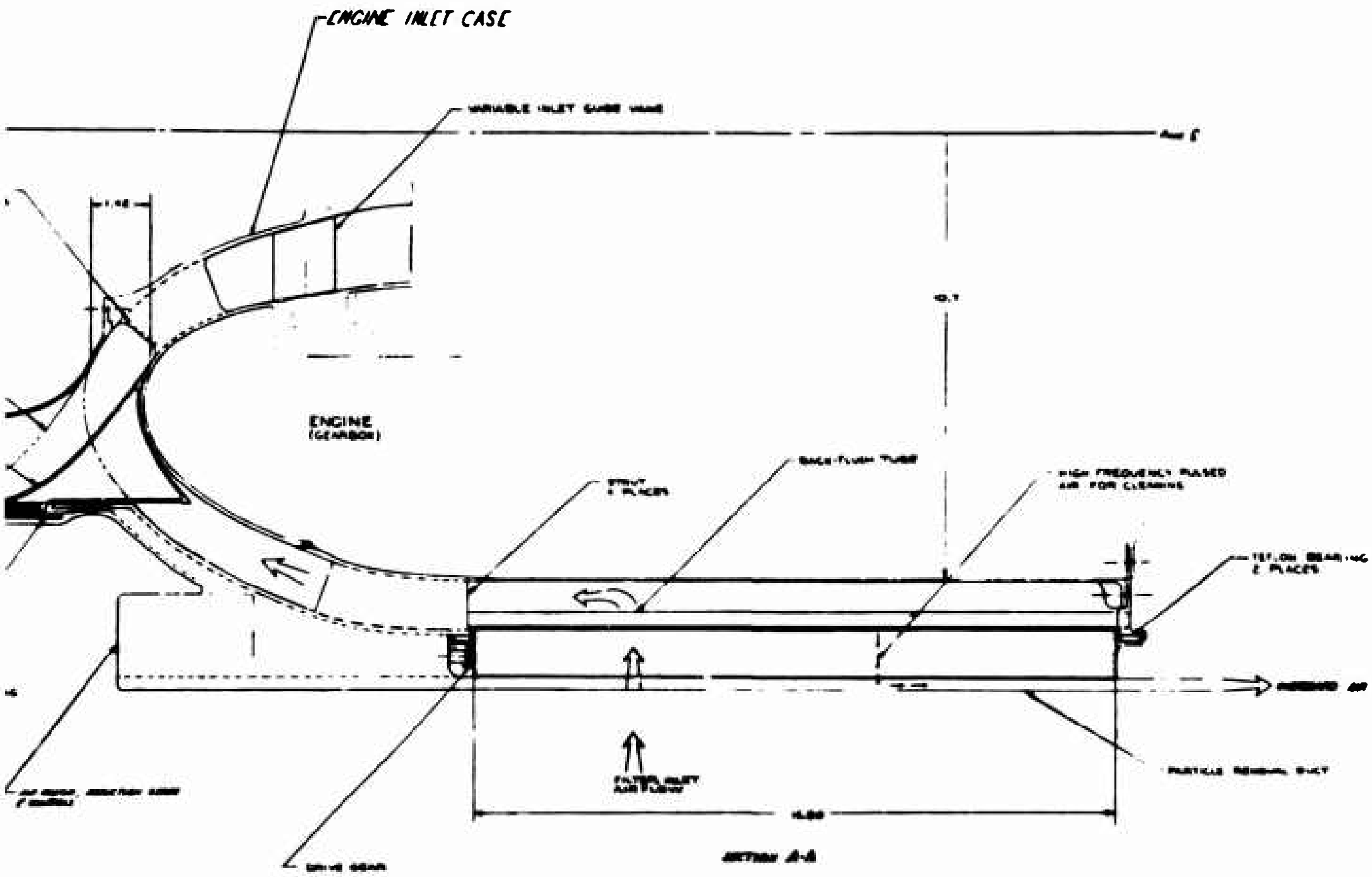



Figure 6. Self-Cleaning Barrier Filter Conceptual Design.



A


ENGINE INLET CASE
VARIABLE INLET GUIDE VANE
ENGINE (GEARBOX)
BACK-FLUSH TUBE
HIGH FREQUENCY PULSED AIR FOR CLEANING
TEFLON BEARING 2 PLACES
PARTICLE REMOVAL DUCT
FILTER INLET AIR FLOW
DRIVE GEAR
SECTION A-A

Investigation of this concept revealed that there are two basic types of electrostatic precipitators: a relatively high-voltage (in excess of 100,000 volts) single-stage type and a lower voltage two-stage type. The single-stage type was ruled out due to the very high voltage and intense corona discharge that would cause radio interference. The two-stage type has been used in radio and TV stations with no electromagnetic interference effects.

A two-stage electrostatic precipitator consists of an ionization section and a precipitator section. The flow area of this type unit is generally sized for approximately 6-7 ft/sec air velocity. The ionization section is used to charge the particles. It consists of 0.007-in.-diameter tungsten wires spaced between ground plates that are 2 in. apart. The plates are operated at a field strength of 10,000 volts/inch and at a current of 100 microamps/ft of wire. A positive electrode is employed to minimize ozone generation; but if ozone were not a consideration, utilizing a negative electrode would produce two to three times more efficient ionization but with seven times more ozone. It was felt that the airflow rate through the ionization section could be increased an order of magnitude, providing negative ionization were employed and the field strength increased to 20,000 - 30,000 volts/inch and the current increased to 200 - 400 microamps/ft of wire.

The precipitator section in commercially available units consists of thin plates spaced approximately 0.250 inch apart that are charged to 5000 volts or 20,000 volts/inch. The plates are 12 inches long and essentially collect all particles.

Using the above information, an electrostatic diversion inlet particle separator was devised. A reduced-scale preliminary design sketch is presented as Figure 7. Incoming particles are charged and electrostatically diverted to the OD where they are collected in the scavenge annulus. Both the ionization section and diverting section operate at 20,000 volts and are supplied by a piezoelectric crystal power supply. The power supply consists of 0.146 pound of piezoelectric material arranged in three crystal packages connected 120 degrees out of phase.

The inlet area is sized for approximately 60 ft/sec airflow velocity, or approximately an order of magnitude increase over standard practice. Sizing the ionization section inlet for this velocity resulted in an OD of approximately 19 inches, which is considered to be compatible with a 8-lb/sec engine. The ionization wires were arranged in a radial pattern. The lightest and most compact arrangement for electrostatically diverting the particles was considered to be an annulus located at the mean inlet area diameter. By providing a 1-inch difference between the ID and the OD radii, a 20,000 volt/inch field strength could be maintained.

The particle trajectory computer program was utilized to determine the concentration effect of the 1-foot-long electrostatic diverting section. The results, shown in Figure 8, indicate minimal concentration effect, primarily due to the 350 ft/sec velocity in the diverting section.

Another configuration was evaluated with the particle trajectory computer program. It consisted of a sufficient number of concentric, annular, 1-inch diverting sections to reduce the velocity in the diverting section to that of the ionization section, 60 ft/sec. The results for one of the annular diverting sections, shown in Figure 9, indicate that there is little increase in particle diversion.

It is concluded that for electrostatic diversion to work, the air velocity would have to be further reduced. This would result in a significant volume increase which might be impractical for helicopter applications.

## PRELIMINARY CONCEPT DESIGN 3 - DIFFUSER INTERSTAGE SEPARATOR

The ST9 advanced-technology engine being tested by P&WA under AVLABS contract has a centrifugal first-stage compressor and a pipe diffuser. For this particular configuration, one way of integrating a separator and the engine would be to use the first-stage centrifugal compressor as a centrifuge. A reduced-scale preliminary design sketch of a concept that uses the interstage diffuser tubes to separate the sand and dust particles is presented as Figure 10. The concept utilizes the strong centrifugal field generated by the radial outflow impeller to force the sand and dust particles through discharge ports appropriately positioned on the outside radius of the diffuser interstage tubes.

There would be no performance loss with this concept because compressor bleed air would not be required to carry the particles through the discharge ports. Instead, separation would depend on the kinetic energy imparted to the particles by the impeller. The particle collection and storage chamber would be of sufficient capacity so that for most applications it would only have to be vented at the end of each mission as a part of engine shutdown procedures.

One difficulty with this concept is that in passing through the compressor, the sand and dust would erode the impeller and diffuser. Two 10-hour ST9 compressor sand-ingestion tests with AC coarse dust (0.0015 $gm/ft^3$) have indicated minimal erosion of the first-stage flow-path hardware with one exception. A region of severe erosion occurred on the pressure surface at the OD of the full blades. However, there is the possibility that the durability of the impeller and diffuser hardware could be significantly improved with coatings that are currently under investigation.

It is also feasible that this concept be employed downstream of another separator. The first separator would remove the coarse particles to a level at which the rotor and diffuser could tolerate the remaining particles. The interstage diffuser discharge ports would then remove the finer particles so that they would not form a glazing deposit after passing through the burner section of the engine.

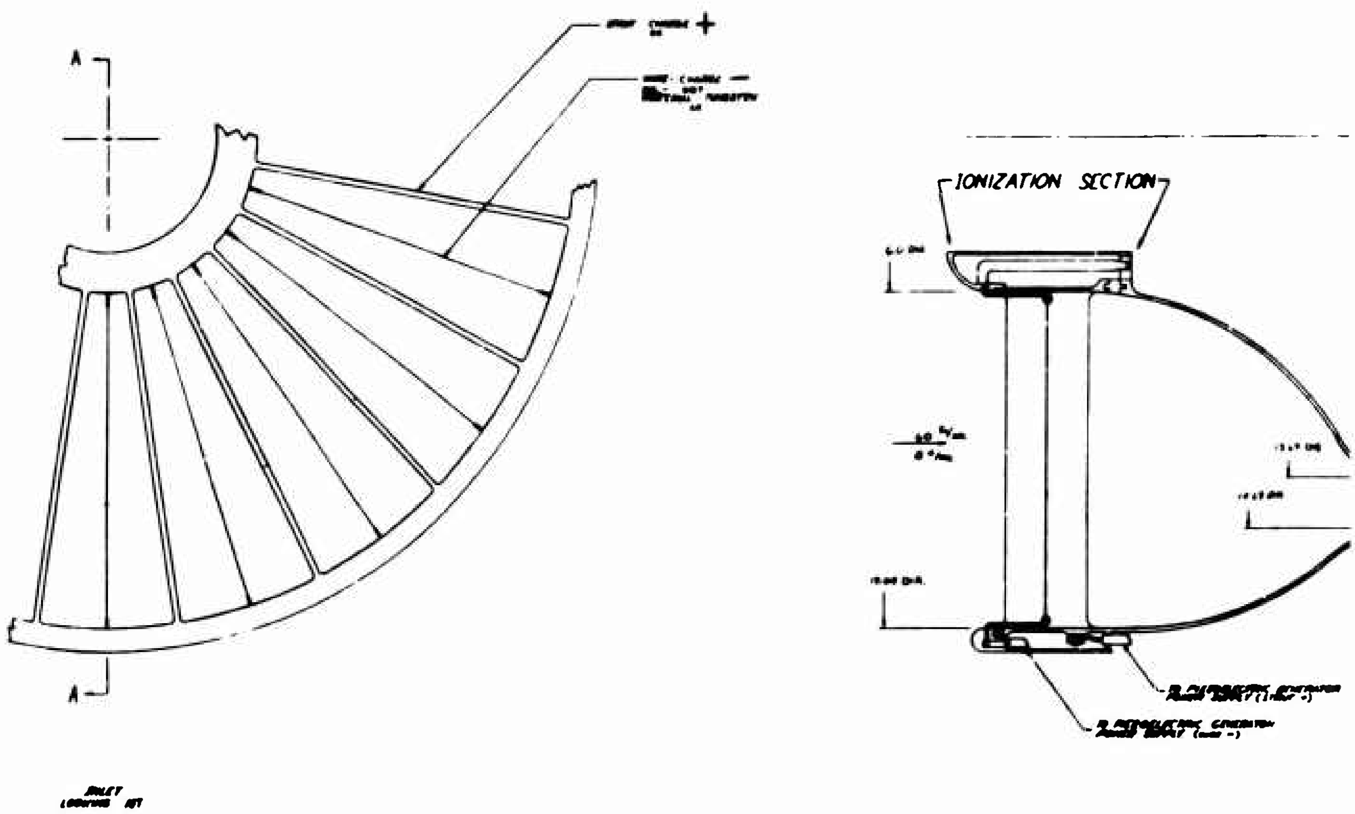
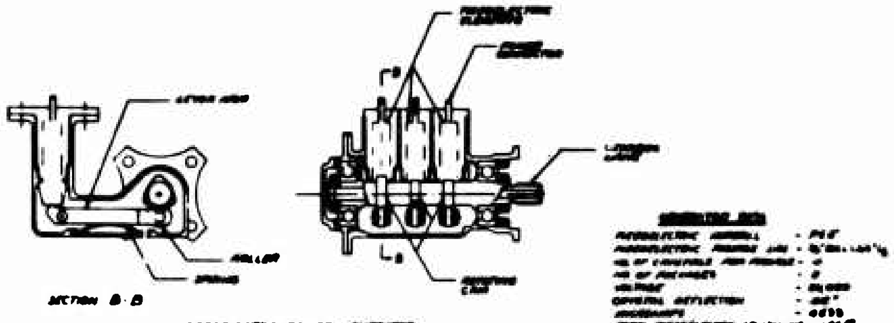



Figure 7. Electrostatic Diverting Separator Conceptual Design.

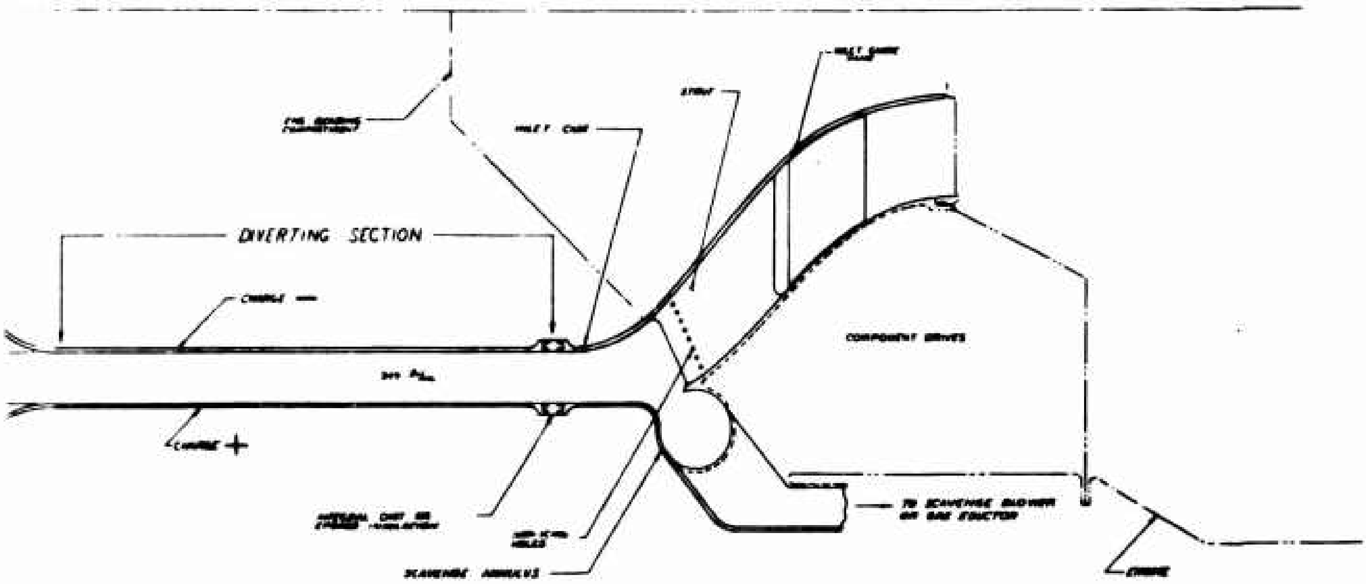


A




SECTION B-B

PIEZOELECTRIC POWER GENERATOR GEARBOX DRIVEN




SECTION A-A

B

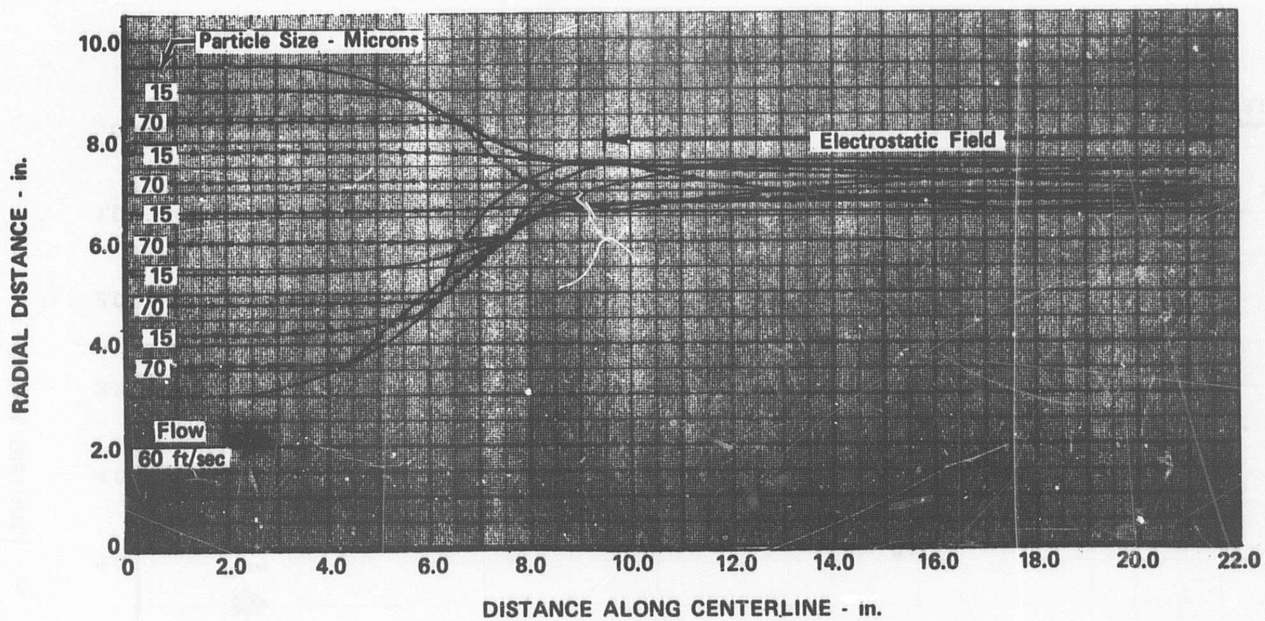



Figure 8. Calculated Particle Trajectories in Electrostatic-Diverting Separator With 20,000 Volts/in. Field Strength.

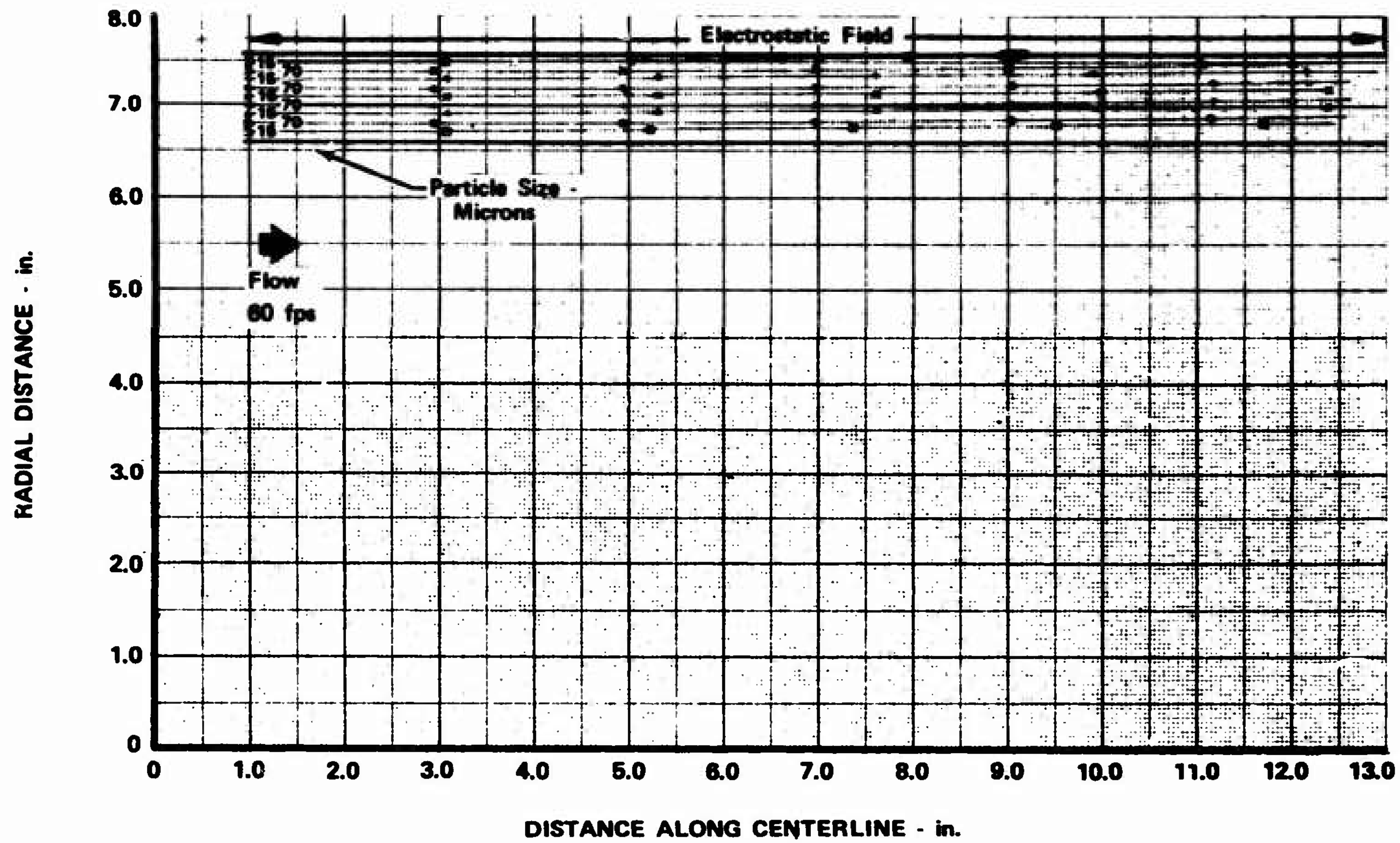



Figure 9. Calculated Particle Trajectories With Reduced Air Velocity Through Diverter Section.

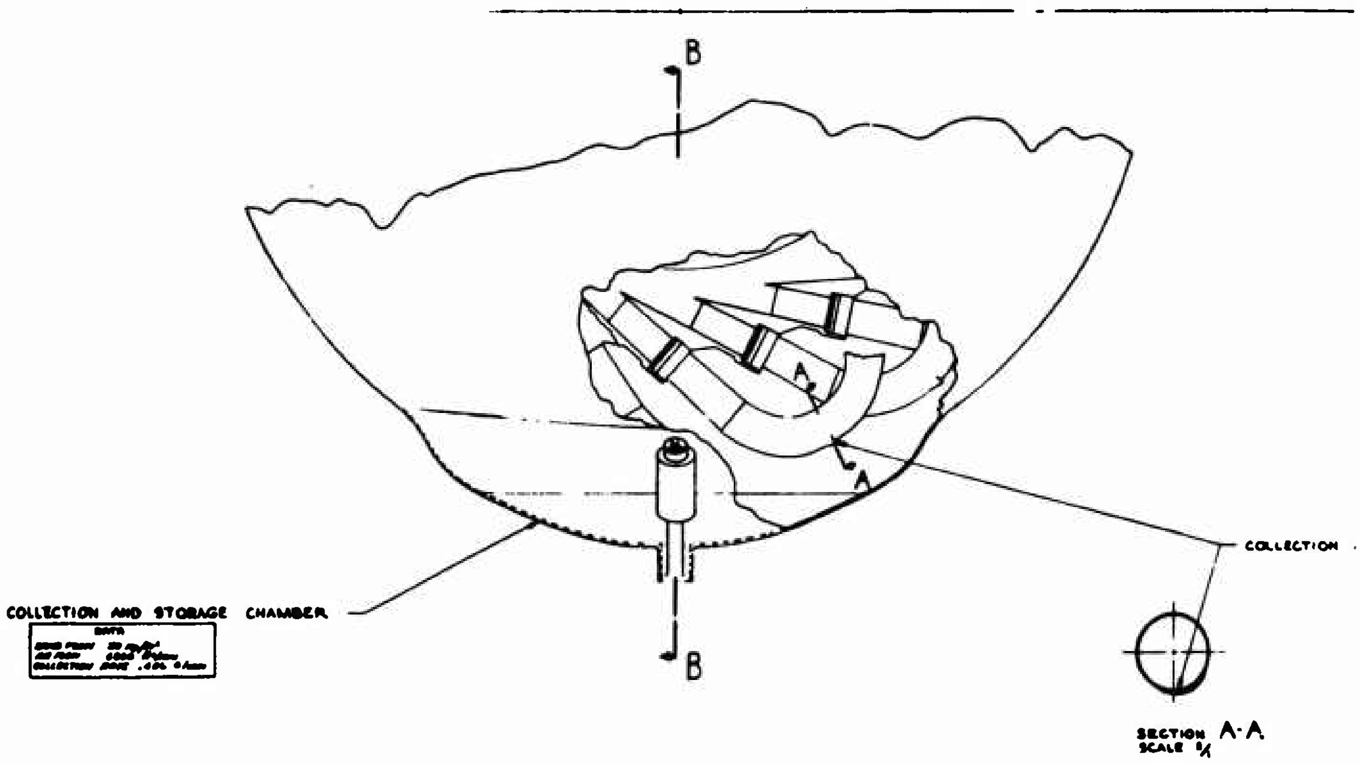
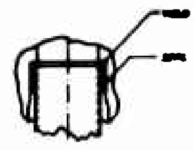
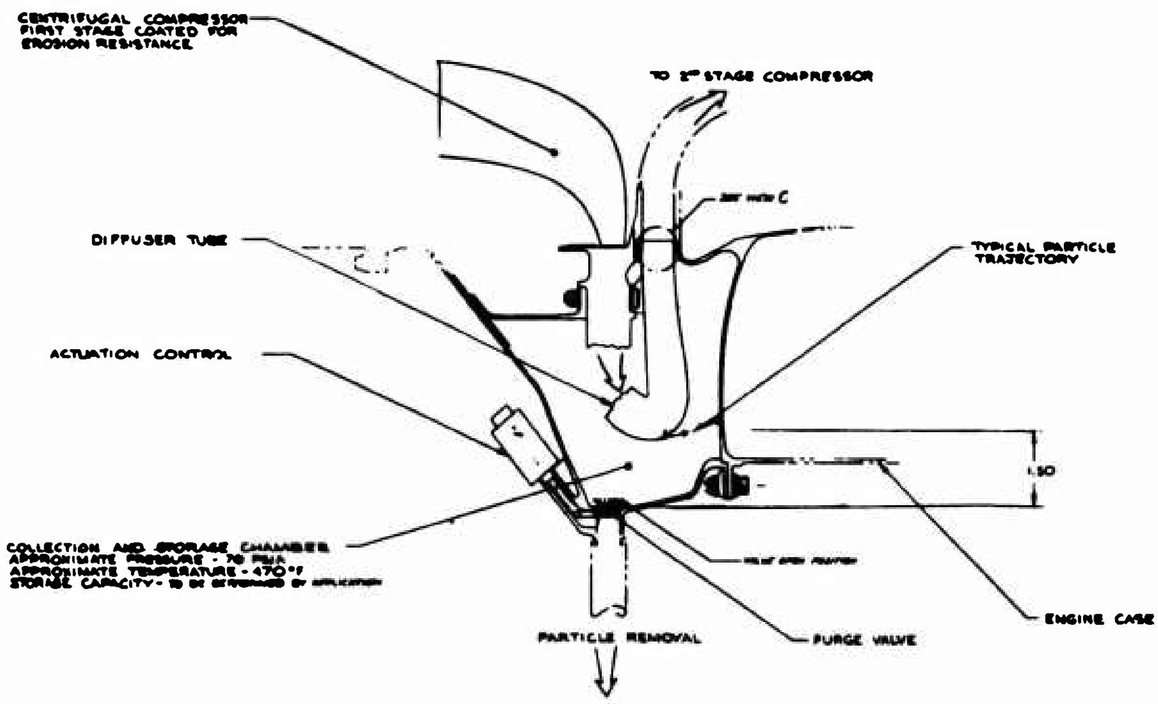



**Figure 10. Diffuser Interstage Separator Conceptual Design.**





CENTRIFUGAL COMPRESSOR FIRST STAGE COATED FOR EROSION RESISTANCE
TO 2ND STAGE COMPRESSOR
SEE VIEW C
DIFFUSER TUBE
TYPICAL PARTICLE TRAJECTORY
ACTUATION CONTROL
1.50
COLLECTION AND STORAGE CHAMBER
APPROXIMATE PRESSURE - 70 PSIA
APPROXIMATE TEMPERATURE - 470°F
STORAGE CAPACITY -
PURGE VALVE
ENGINE CASE
PARTICLE REMOVAL


SECTION B - B

B

## PRELIMINARY CONCEPT DESIGN 4 - INLET INERTIAL SEPARATOR

Conventional right-angle-bend inertial separators tend to incur a penalty in separation efficiency because of particles ricocheting in such a way that their inertia prevents them from being carried off by the scavenge airflow. One approach to correcting this problem would be to provide special particle entrapment zones consisting of deeply chamfered boundary layer bleed slots, as described in Reference 8. However, this concept was rejected as being too prone to clogging of the bleed slots.

An alternative approach would be to control particle ricochet in order to maximize particle concentration. A reduced-scale preliminary design sketch of this approach is presented in Figure 11. The concept utilizes a parallel wall circumferential inlet in order to provide consistent particle trajectories at the bottom of the right-angle bend where the dust particles are concentrated and can then be captured in a collection annulus.

The previously described particle-trajectory computer program was used to evaluate the effect of changing inlet wall spacing and flow turning angle. A particle trajectory plot for an inlet inertial separator having a 72-degree flow-turning angle and an inlet velocity of 170 ft/sec is shown in Figure 12. Another particle-trajectory plot shown in Figure 13 is for an 80-degree flow turning angle and decreased wall spacing which increased the inlet velocity to 250 ft/sec. By comparing the two plots, it can be seen that increasing the flow turning angle and inlet velocity tends to maximize particle concentration at the bottom of the duct. High inlet velocity, however, results in increased pressure drop and resultant power loss. A toroidal diverter is included in the concept to allow for ram air pressure recovery. The penalty in engine power can be avoided, when separation is not required, by positioning the toroidal diverter in the ram inlet position.

## PRELIMINARY CONCEPT DESIGN 5 - ROTATING-FILAMENT SEPARATOR

The feasibility of using rotating brushes or filaments for particle separation has been investigated by Illinois Institute of Technology Research Institute (IITRI) in a program conducted for Naval Air Systems Command (Reference 9). This concept uses disk-shaped brushes mounted on a rotating shaft to produce centrifugal and impaction separation forces. The brush assembly is depicted in Figure 14. Tests have demonstrated that a separation efficiency of approximately 89% can be obtained by rotating three 13.5-in.-diameter brushes at 1480 rpm, which required 0.58 hp to pass 1.08 lb/sec. The power required to pump the purge air overboard was not included in the data since the tests were conducted in a duct supercharged above ambient pressure by a blower. At 8 lb/sec flow rate, however, the volume and perhaps the weight of such a configuration would be prohibitive. An alternative approach for increasing flow capacity would be to force more flow through the prototype unit. Interpolating test data for the higher flow rate produced a very poor separation efficiency of approximately 50%.

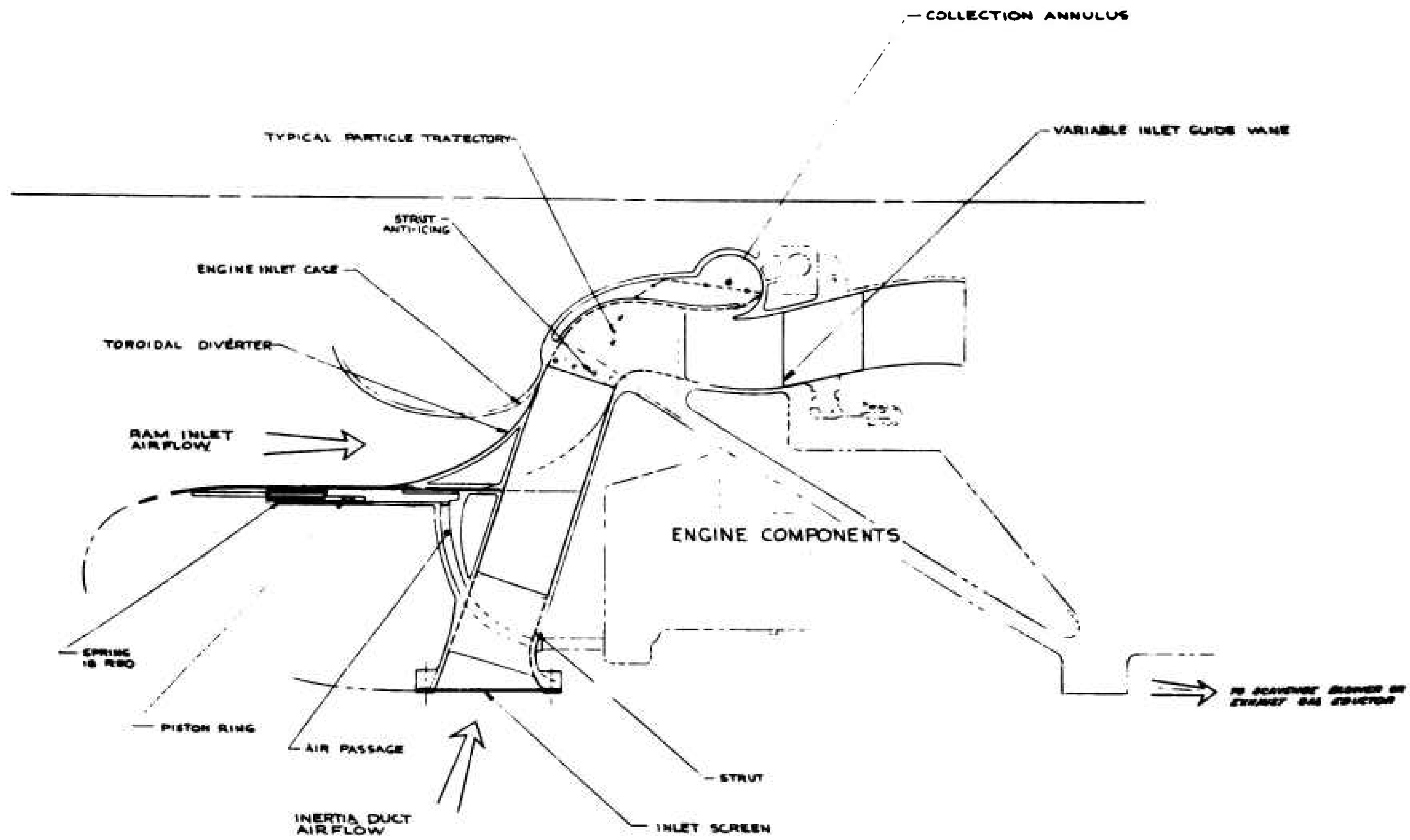



Figure 11. Inlet Inertial Separator Conceptual Design.

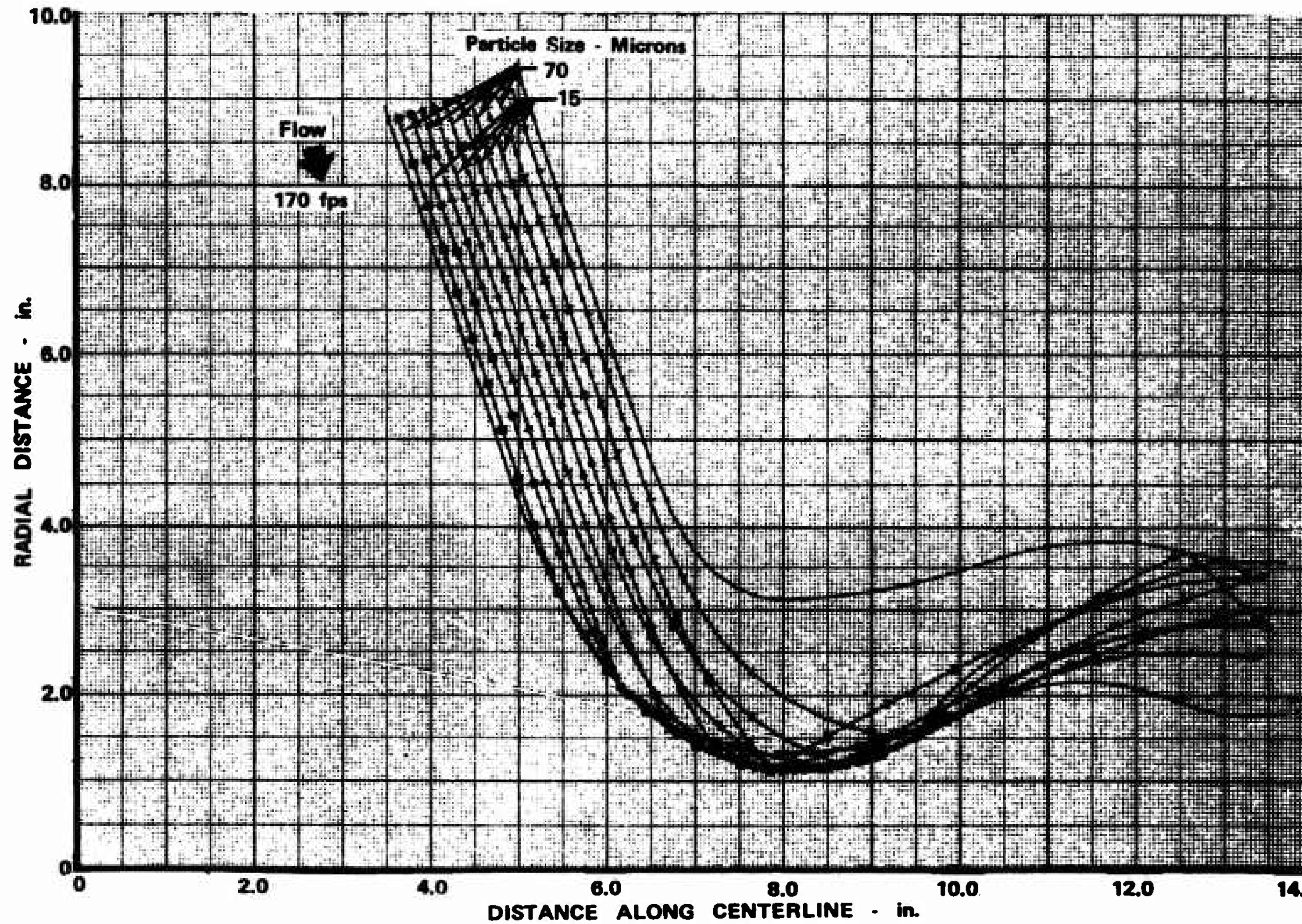



Figure 12. Calculated Particle Trajectories in 72-Degree Inlet Inertial Separator.

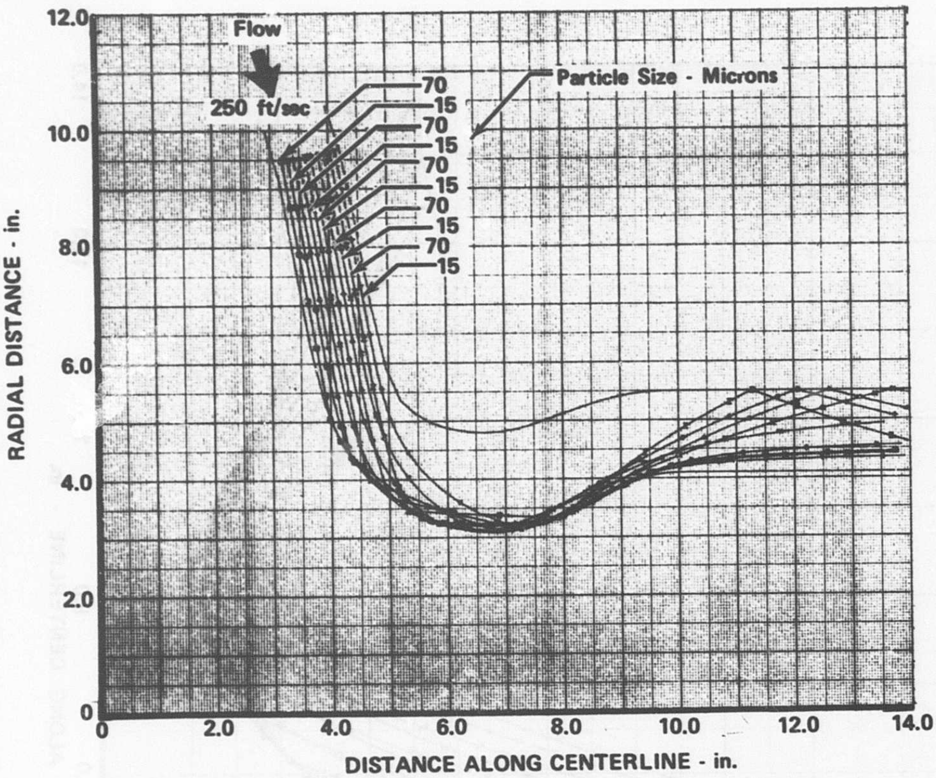



Figure 13. Calculated Particle Trajectories in 80-Degree Inlet Inertial Separator.

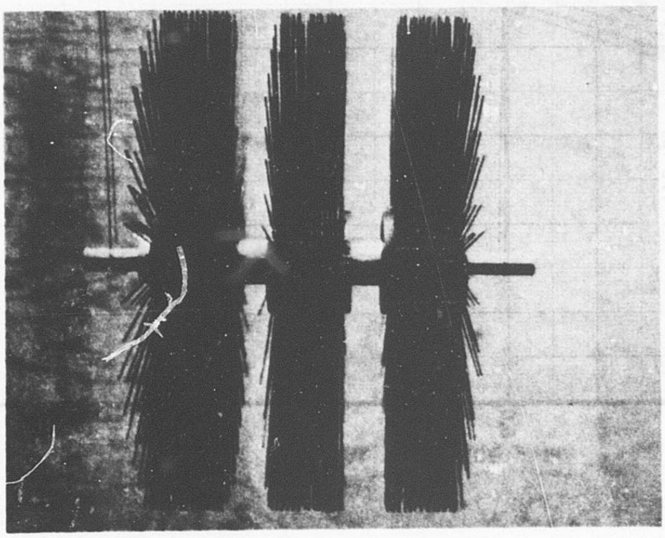


Figure 14. Rotating Brush From IITRI Particle Separator.

To gain further knowledge, a visit was made to IITRI, Chicago, to discuss the most recent thinking on rotating brush design. One major change to the brush system would be to have the wires angled away from the direction of rotation, instead of radially oriented. It was felt that this would improve the particle separation efficiency associated with impaction. During IITRI's limited amount of testing, no measurable erosion of the 1.0-mm-dia. wires occurred; however, severe fatigue at the wire roots was encountered due to vibration. It was suggested that restraining the wire tips with a shroud should greatly reduce the wire vibration problem. The shroud would have to be carefully designed to permit dust particles to pass through without causing an unequal dust buildup that would affect balance. To rotate their brush test model, IITRI utilized a hydraulic drive system which limited test speeds to approximately 2000 rpm. Theoretically, increased operating speeds should improve separation efficiency.

The design approach taken for integrating a rotating-filament separator with an engine was based upon IITRI's experience and recommendations for making improvements. A reduced-scale preliminary design sketch of a rotating-filament separator integrated with an 8 lb/sec engine is presented in Figure 15. For this concept, the separator is located in front of the inlet guide vanes and rotates at free-turbine shaft speeds. The separator consists of a number of filament and shroud assemblies stacked together. Space is provided between each shroud for particles to pass through into the scavenge annulus.

The particle trajectory computer program was used to evaluate the separator length that might be required if the particles were centrifuged to the OD solely by gas swirl centrifugal force. The particle trajectory plot shown in Figure 16 indicates that particles flowing through a duct with a 75-degree swirl component would require more than a 12-inch length for all particles to be centrifuged to the OD. In an actual rotating-filament separator, considerable particle impaction would occur, but it was not possible to simulate this effect with the particle trajectory computer program. It is estimated that if the combined effects of centrifugal and impaction forces were considered, the length of separator required to provide good separation efficiency would be significantly less than 12 in.

Due to the deficiency of current design information, additional exploratory research is recommended prior to actually designing and testing a unit that would be operating at a speed that is an order of magnitude greater than the original prototype.

## PRELIMINARY CONCEPT DESIGN 6 - SEMI-REVERSE-FLOW SEPARATOR

The review of current separator configurations in Task 1 led to the idea of combining features of both the United Aircraft of Canada Ltd. inertial separator intake and the Wright-Patterson Aerospace Research Labs semi-reverse-flow swirl chambers.

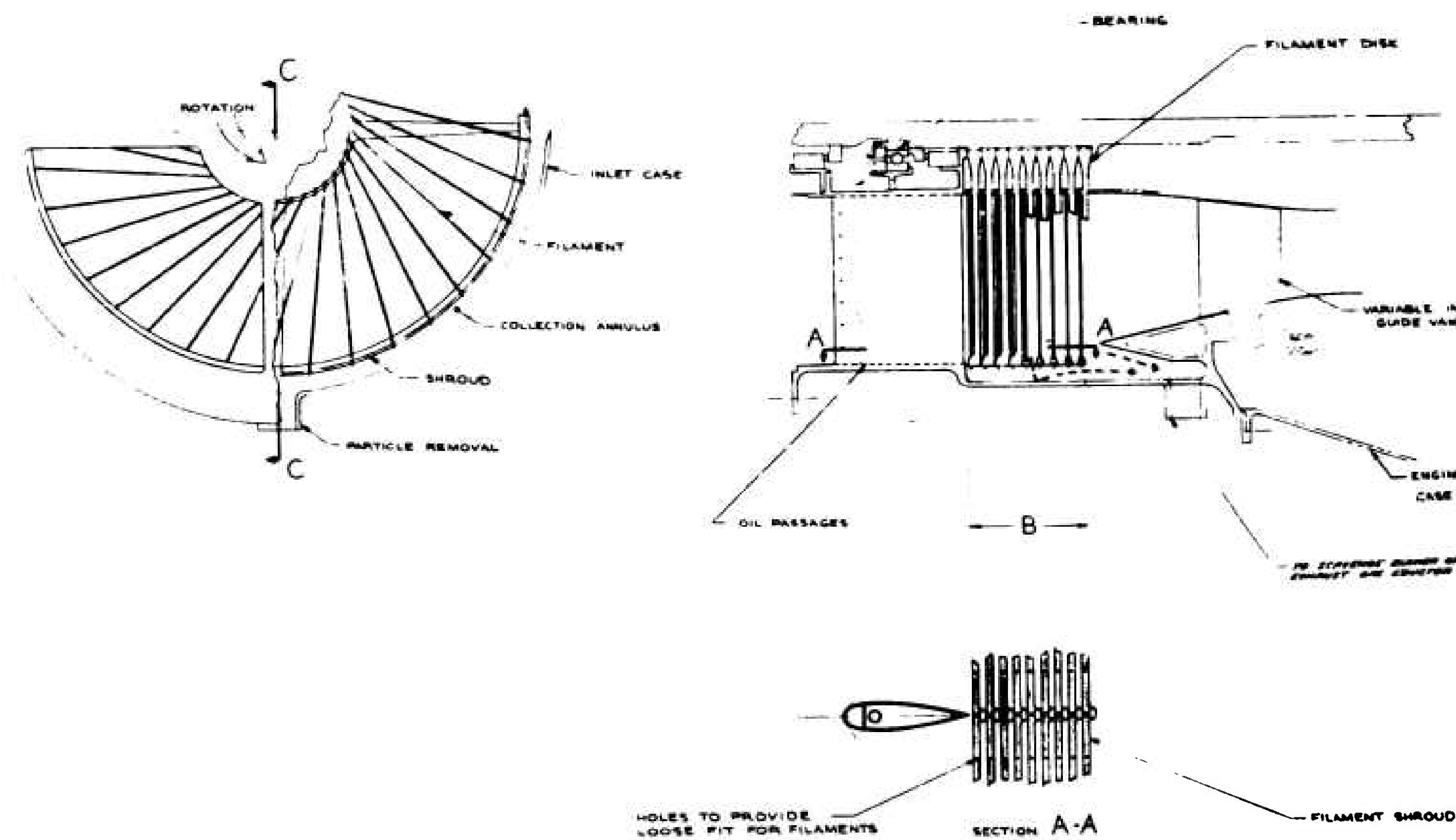



Figure 15. Rotating-Filament Separator Conceptual Design.

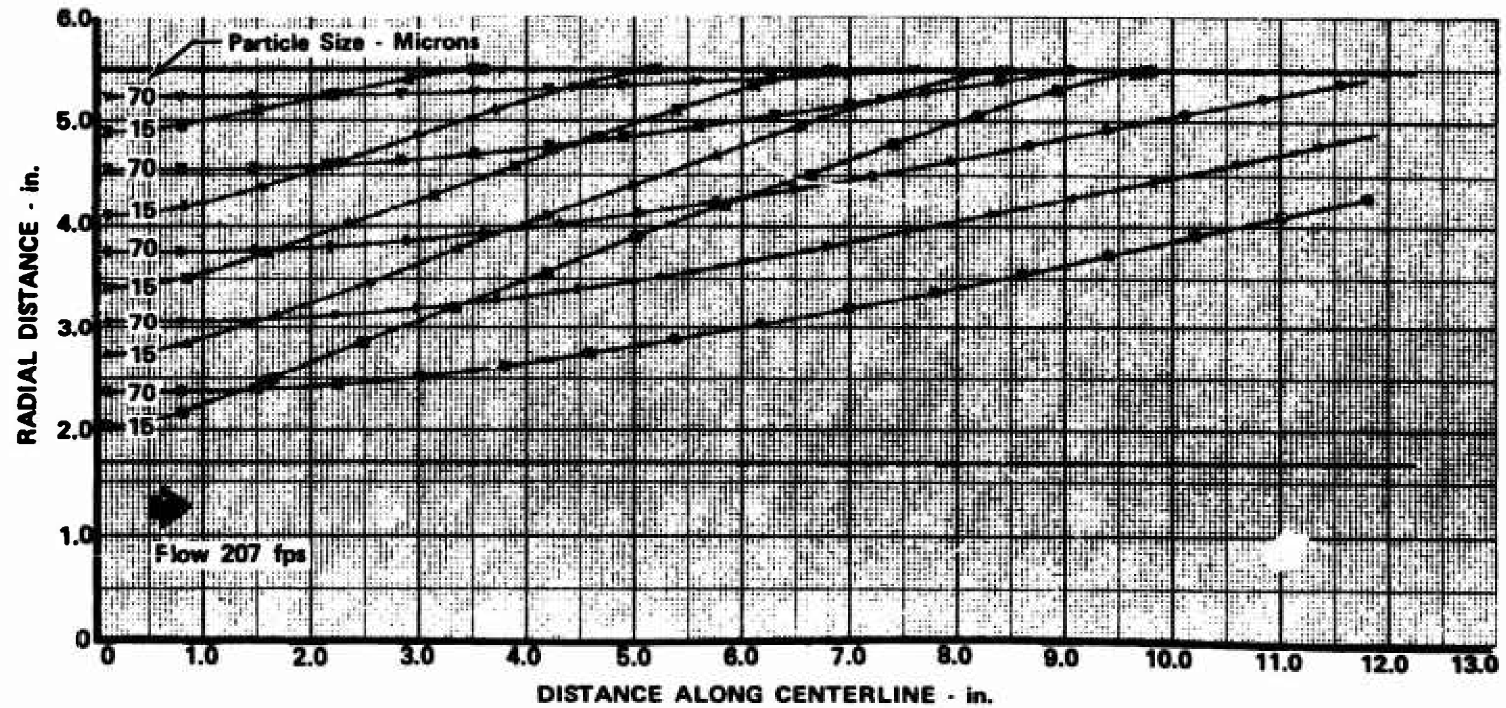



Figure 16. Calculated Particle Trajectories in Rotating-Filament Separator With Simulated 75-Degree Gas Swirl.

The latest version of the UACL inertial separator intake is designed for use in the Bell Model 212 helicopter. A schematic of the twin PT6T-3 engine installation and inertial separator intake system is shown in Figure 17. In this installation, separator bypass flow is produced by using the gas generator exhaust stub as the primary nozzle of an exhaust gas eductor system in the bypass duct. Test results have indicated separation efficiencies as high as 80% with AC coarse dust at approximately 8 in. $H_2O$ pressure drop and at a bypass scavenge flow equivalent to 40% of engine airflow. The inertial separator intake has been tested in icing and snowfall conditions throughout the flight power range without adverse effect on engine operation or serious loss of power. The intake system has also been tested with other materials such as grass, leaves, crushed rock and pieces of ice, all of which were separated with 100% success.

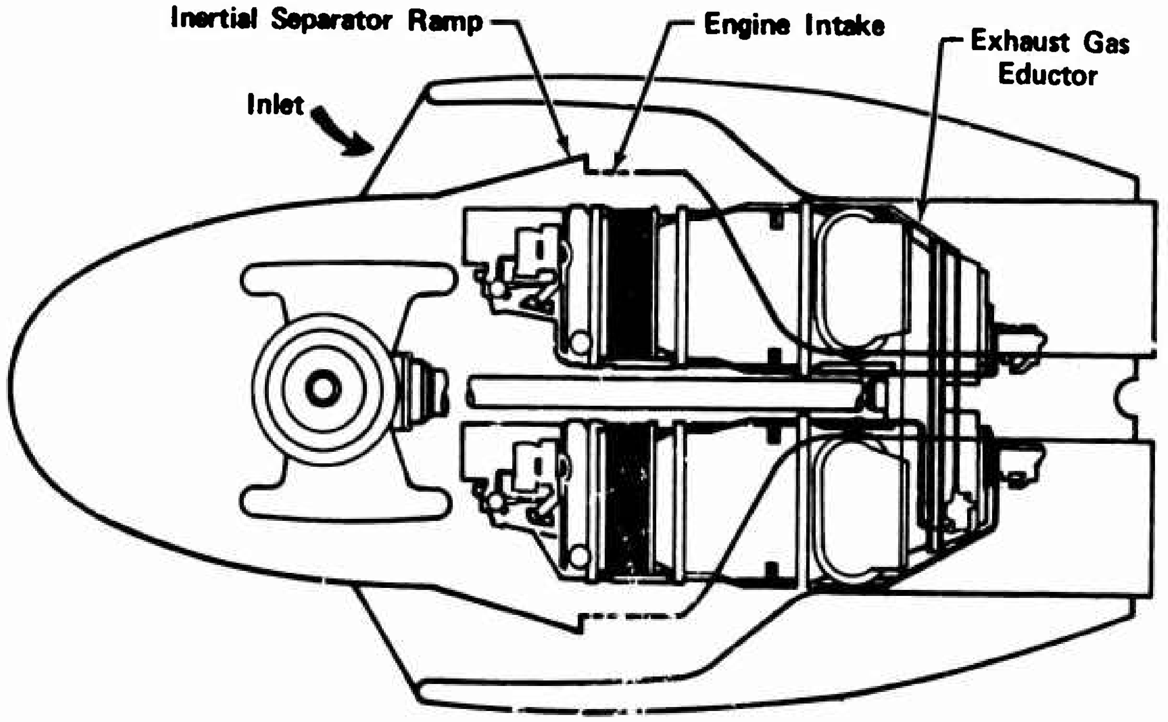



Figure 17. United Aircraft of Canada, Ltd., Bell 212 Inertial Separator Intake Installation.

The semi-reverse-flow swirl chambers were developed at the Wright-Patterson Aerospace Research Laboratories during a particle separation investigation (Reference 2). A section view of a swirl chamber is presented in Figure 18. The inlet vanes have a 28-degree swirl angle, and the diffuser outlet has 35-degree deswirl vanes. Of the vortex tubes that were examined by Sikorsky in Task 1, the ARL swirl chambers had the highest separation efficiency. A 46-unit cluster has demonstrated 95% separation efficiency on AC coarse test dust at 4 in. $H_2O$ pressure drop and 2-1/2% scavenge flow. The major disadvantage of this unit is that, due to the large hub-tip ratio design, it requires approximately three times as much approach area as other vortex-tube separators.

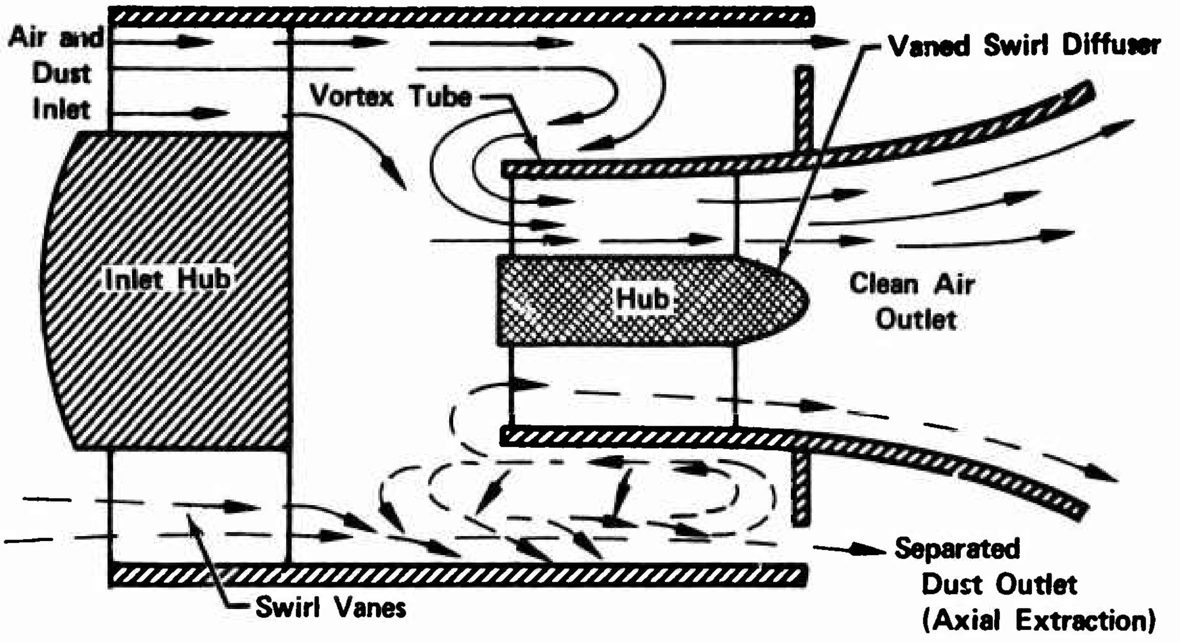



Figure 18. Wright-Patterson Aerospace Research Laboratories Semi-Reverse-Flow Swirl Chamber.

Combining the above two designs led to the semi-reverse-flow separator concept. A reduced-scale preliminary design sketch is presented as Figure 19. In this concept, separation efficiency is improved by introducing swirl in an annular duct which is similar in cross section to the UACL two-dimensional separator. By utilizing an exhaust gas eductor to produce the required scavenge flow, the semi-reverse-flow concept offers a reliable low maintenance particle separator which has no moving parts and which could be an integral part of the engine inlet case.

PRELIMINARY CONCEPT DESIGN 7 - POWERED MIXED-FLOW SEPARATOR

The use of a powered centrifuge for particle separation purposes was first considered at Pratt & Whitney Aircraft as a potential "add-on" modification to a J52 engine for Heavy Lift Helicopter (HLH) application. A powered centrifuge also offers the potential of being an integral part of an engine from its conception. The pressure rise from the separator stage would contribute to the overall engine cycle pressure ratio.

A reduced-scale preliminary design sketch of an integral powered mixed-flow separator is presented as Figure 20. The impeller would be driven at engine speed to eliminate the weight penalty associated with a speed-reducing gearbox. A mixed-flow impeller was chosen because it combines the high-pressure ratio per stage of a centrifugal compressor with the small outer diameter of an axial-flow compressor. For particle-separation purposes, the turning of the radial outflow from the mixed-flow impeller results in a significant increase in centrifugal force on the dust particles over that induced by an equivalent straight-through axial-flow compressor.

However, the optimum design and location of the annular collection zone may have to be a combined product of analysis and testing. The results of preliminary evaluation of this concept with the particle trajectory computer program, as shown in Figure 21, indicate that a concentration of particles does occur at the duct OD. Of course, a scavenge blower or exhaust gas eductor would not be required since total pressure in the particle collection annulus will be greater than atmospheric and will provide the necessary scavenge bleed flow. The power loss due to scavenge flow is shown in Figure 22; since these losses are essentially proportional to scavenge flow rate, it is desirable to minimize this flow.

In a free shaft engine, two shaft speeds are available: the power-takeoff shaft speed and the gas generator speed. A brief analysis was made to determine the effect of shaft speed on impeller tip diameter. The results, shown in Figure 23 as a function of pressure ratio for two selected shaft speeds, indicate that the higher shaft speed would result in a more compact impeller for a given pressure ratio, and that the minimum pressure ratio for the higher shaft speed would be approximately 1.4 to 1. One problem with operating at these high speeds in a sand and dust environment is that the impeller will experience some erosion damage. However, after a 10-hour sand ingestion test with an ST9 first-stage impeller, the resultant wear was not unreasonable. Before and after test results using an AC coarse test dust concentration of 0.0015 $gm/ft^3$ are shown in Figure 24. An impeller actually designed for use as a separator could have blades with increased thickness in the regions of maximum wear, or coatings might be used to improve erosion resistance.

## PRELIMINARY DESIGN CONCEPT 8 - INTEGRAL VORTEX-TUBE SEPARATOR

An integral vortex-tube separator was of interest for protecting an aircraft gas turbine engine because of the proven effectiveness of currently available vortex-tube elements. A reduced-scale preliminary design sketch of an integral vortex-tube separator is presented as Figure 25. This concept provides a separator comprised of vortex-tube elements and a ram-air bypass duct that can be anti-iced.

Of the vortex tubes studied by Sikorsky Aircraft in Task 1, the 1-in.-diameter short tube was selected because, being only 2.75 in. long, it was the shortest and provided a separation efficiency in excess of 90% on AC coarse test dust. Using information provided by Sikorsky, it was estimated that 408 1/2-inch-diameter vortex tubes would be required to provide a pressure drop of approximately 4 in. $H_2O$. By selecting an OD of approximately 20 in., which would be compatible with an 8 lb/sec engine, it was determined that a separator length of 10.5 in. would be required to accommodate the vortex tubes and necessary scavenge passages. The vortex tubes are arranged in eight clusters to provide the necessary scavenging in accordance with Sikorsky's recommendations. Each cluster of tubes is mounted in a separate framework or module to allow for servicing without disassembling the entire separator.

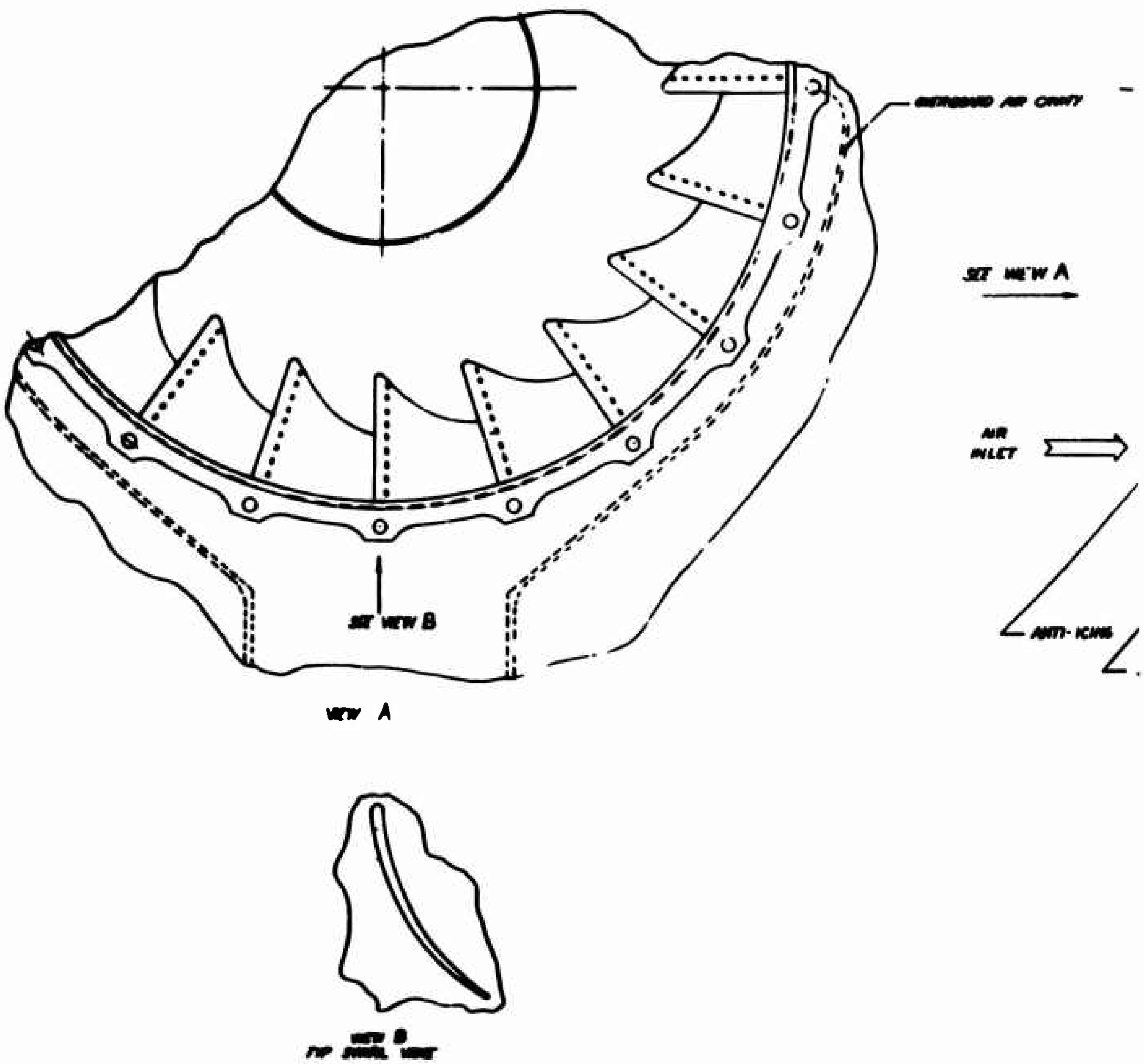
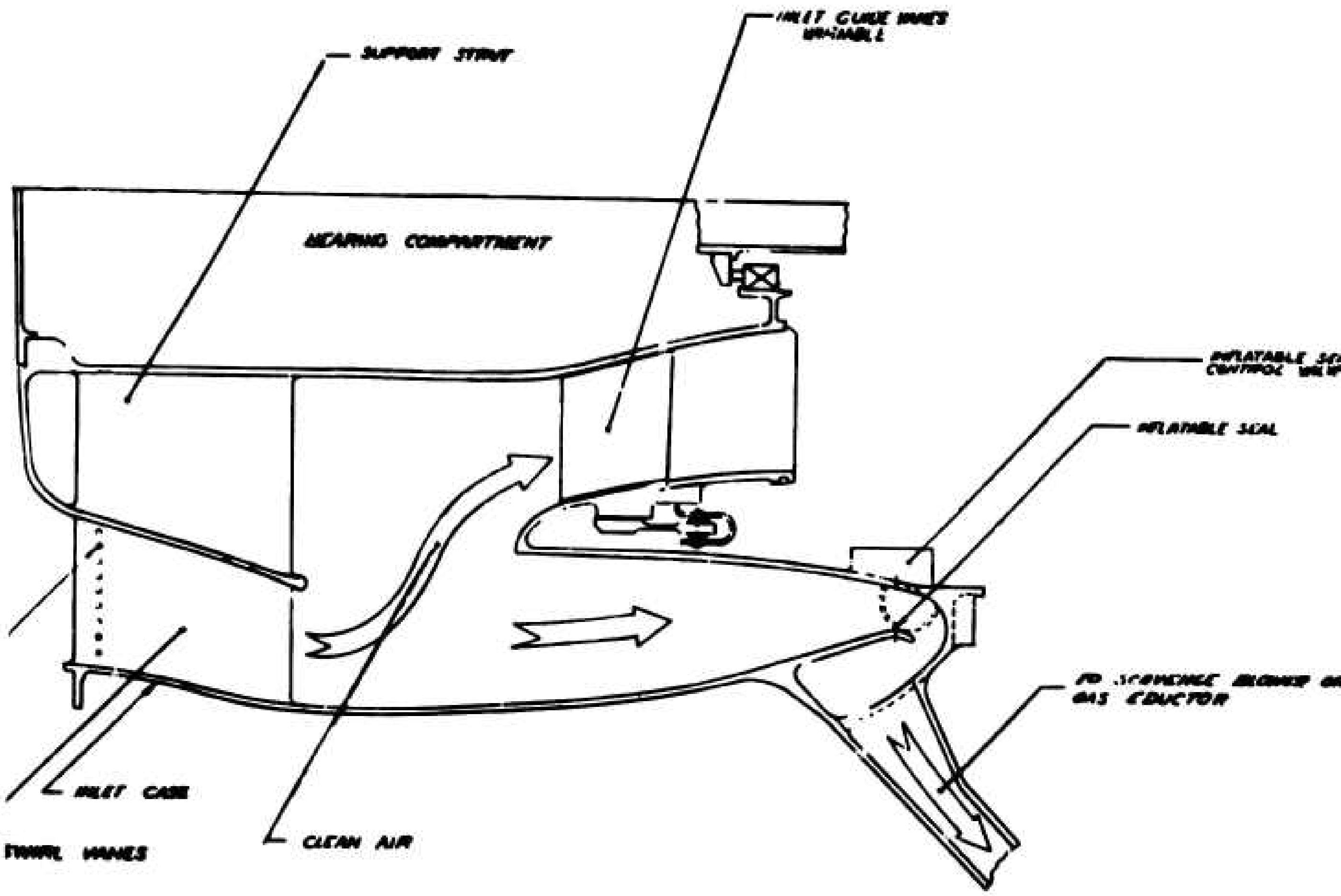



Figure 19. Semi-Reverse-Flow Separator Conceptual Design.


SUPPORT STRUT
INLET GUIDE VANES
BEARING COMPARTMENT
INFLATABLE SEAL CONTROL VALVE
INFLATABLE SEAL
TO SCAVENGE BLOWER OR GAS EDUCTOR
INLET CASE
SWIRL VANES
CLEAN AIR

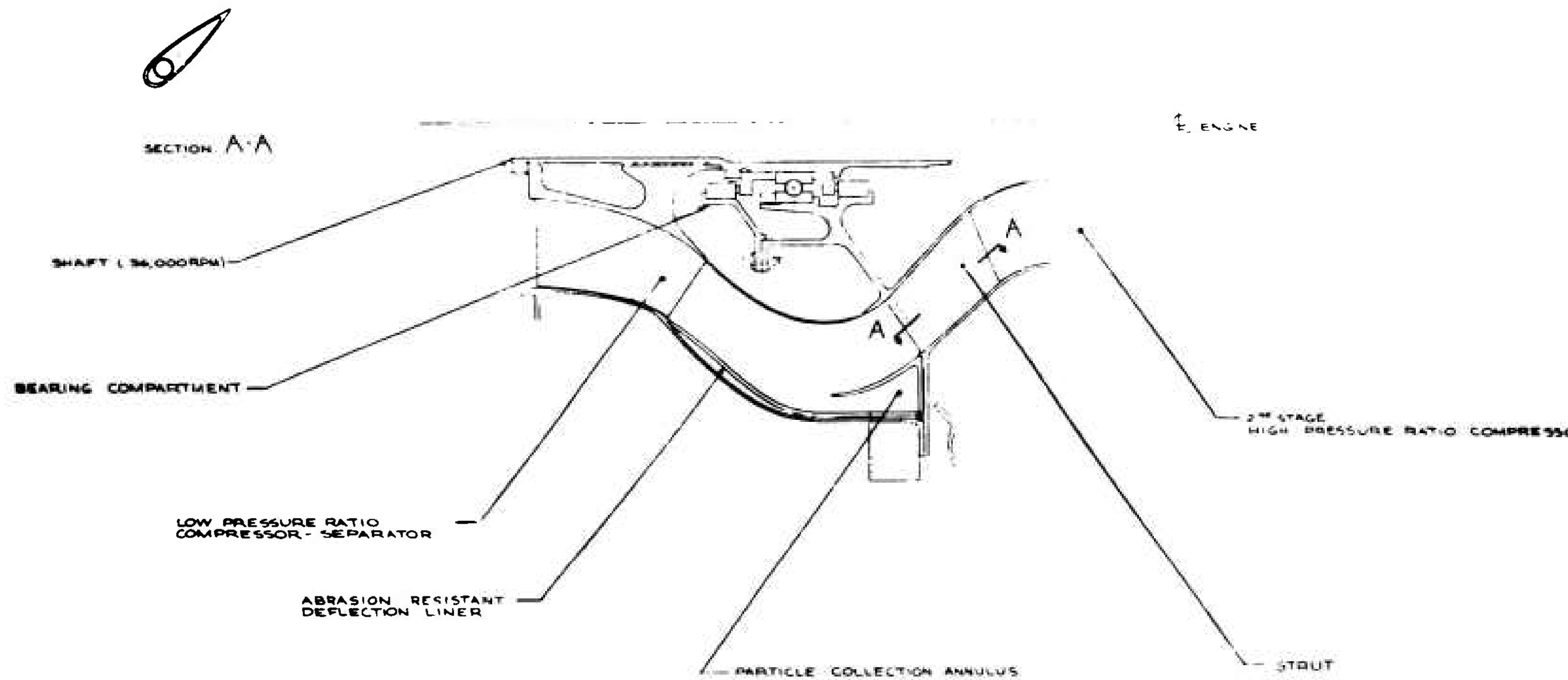



Figure 20. Powered Mixed-Flow Separator Conceptual Design.

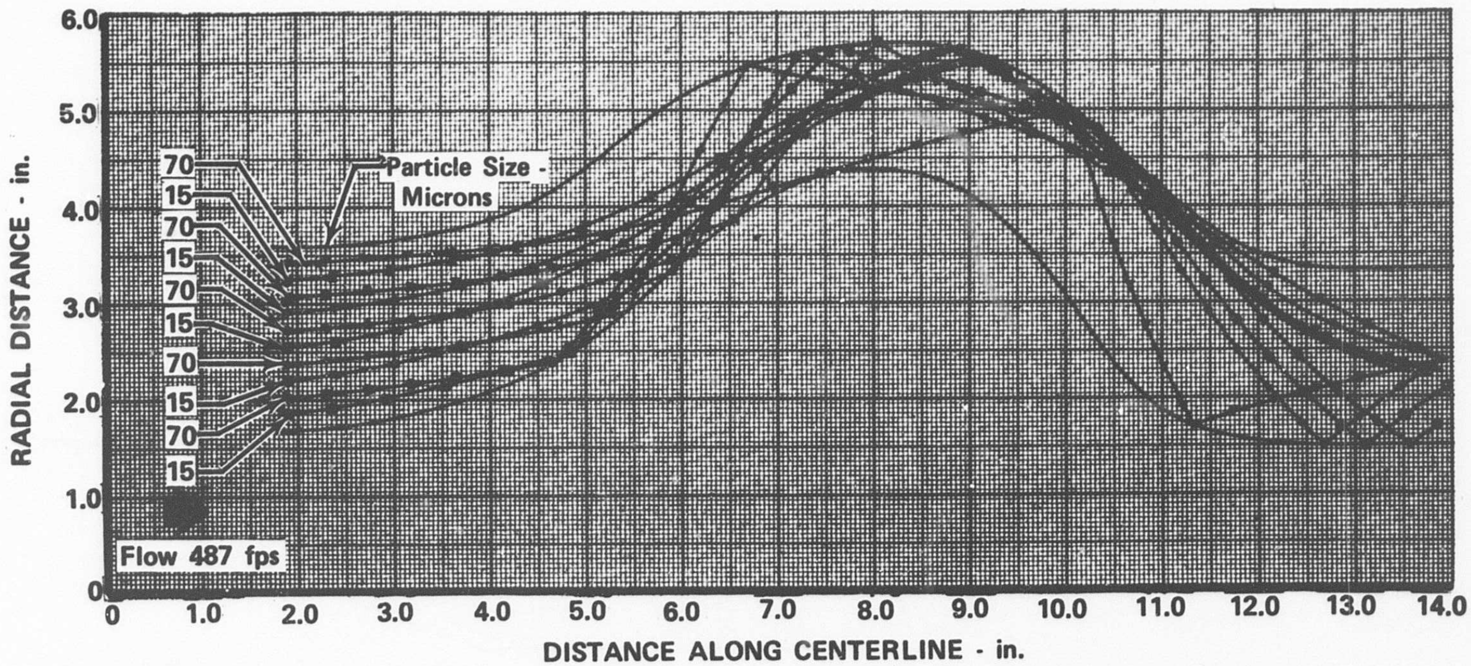



Figure 21. Calculated Particle Trajectories in Powered Mixed-Flow Separator With Simulated 60-Degree Gas Swirl.

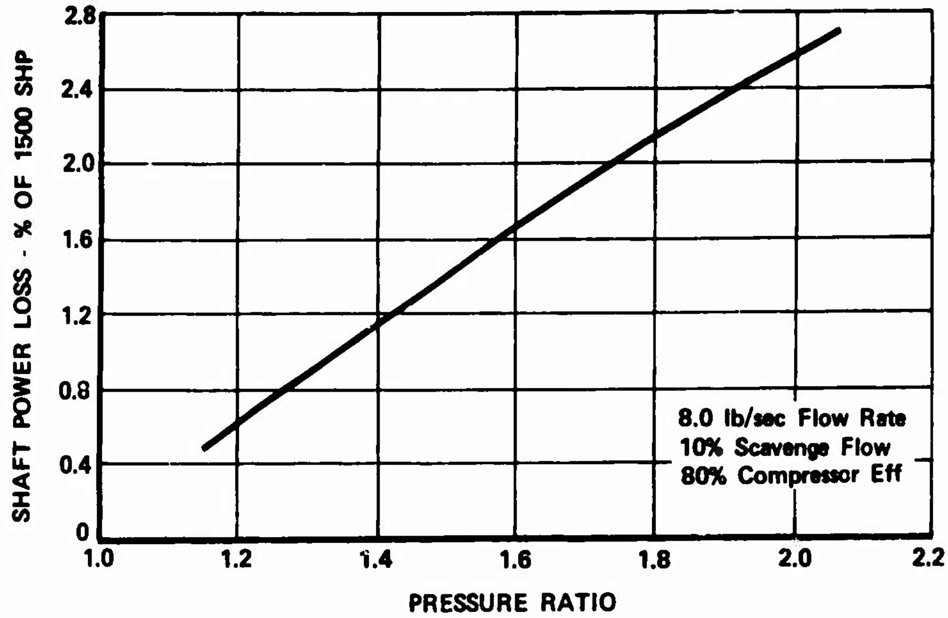



Figure 22. Scavenge Bleed Flow Estimated Power Loss.

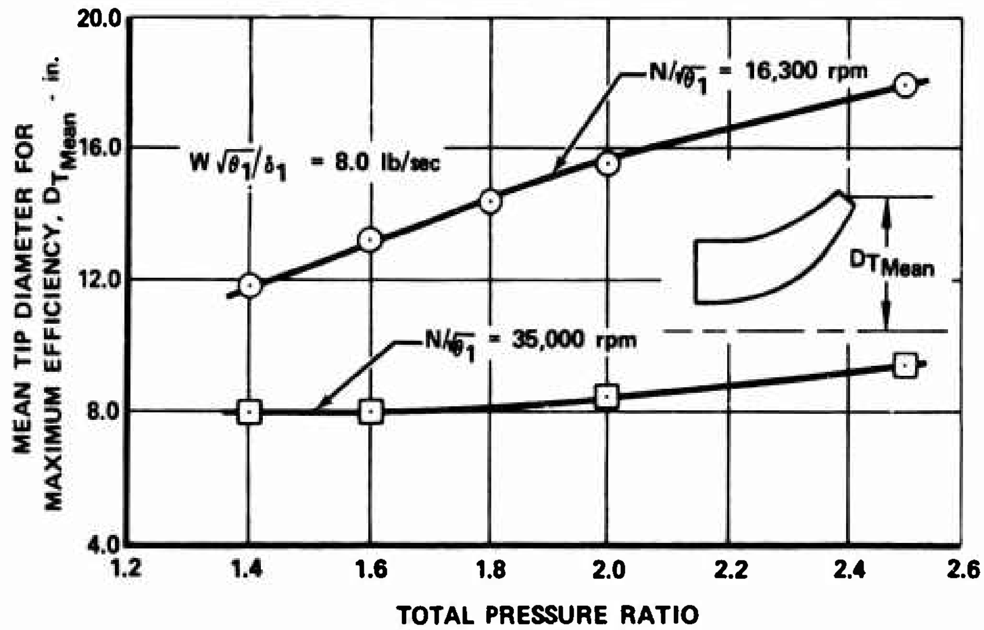



Figure 23. Effect of Speed and Pressure Ratio on Mixed-Flow Impeller Sizing.

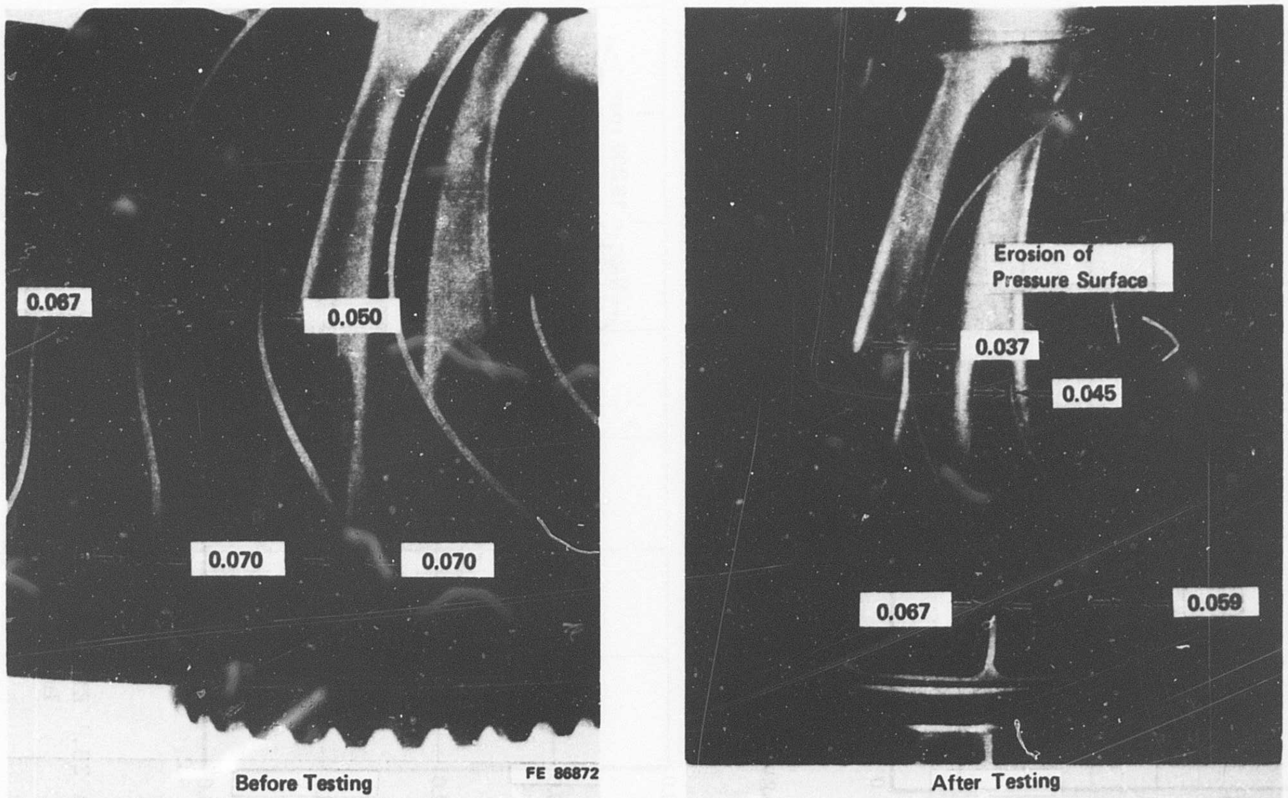



Figure 24. Impeller Wear After Sand Ingestion at 0.0015 $gm/ft^3$ for 10 Hours.

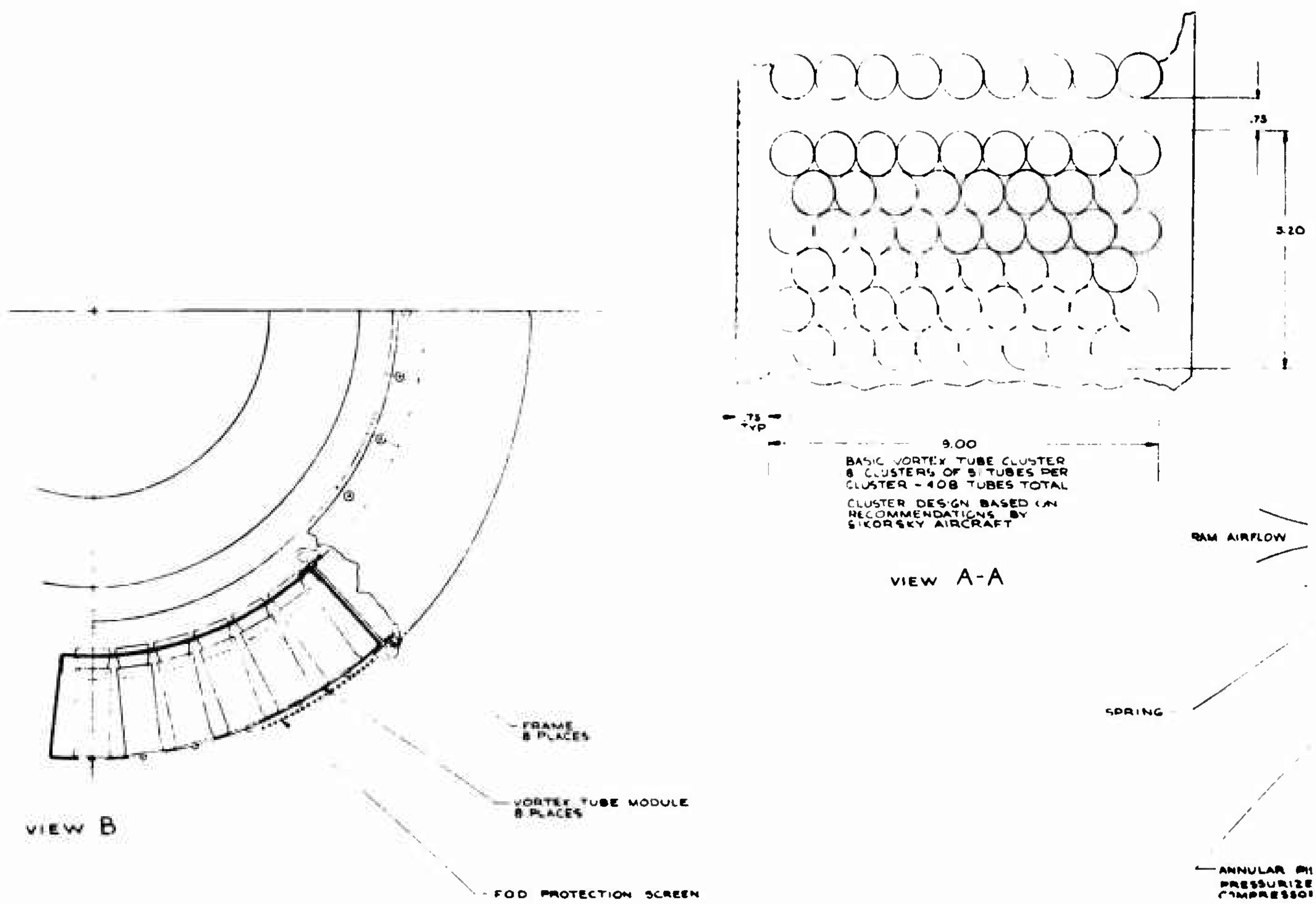
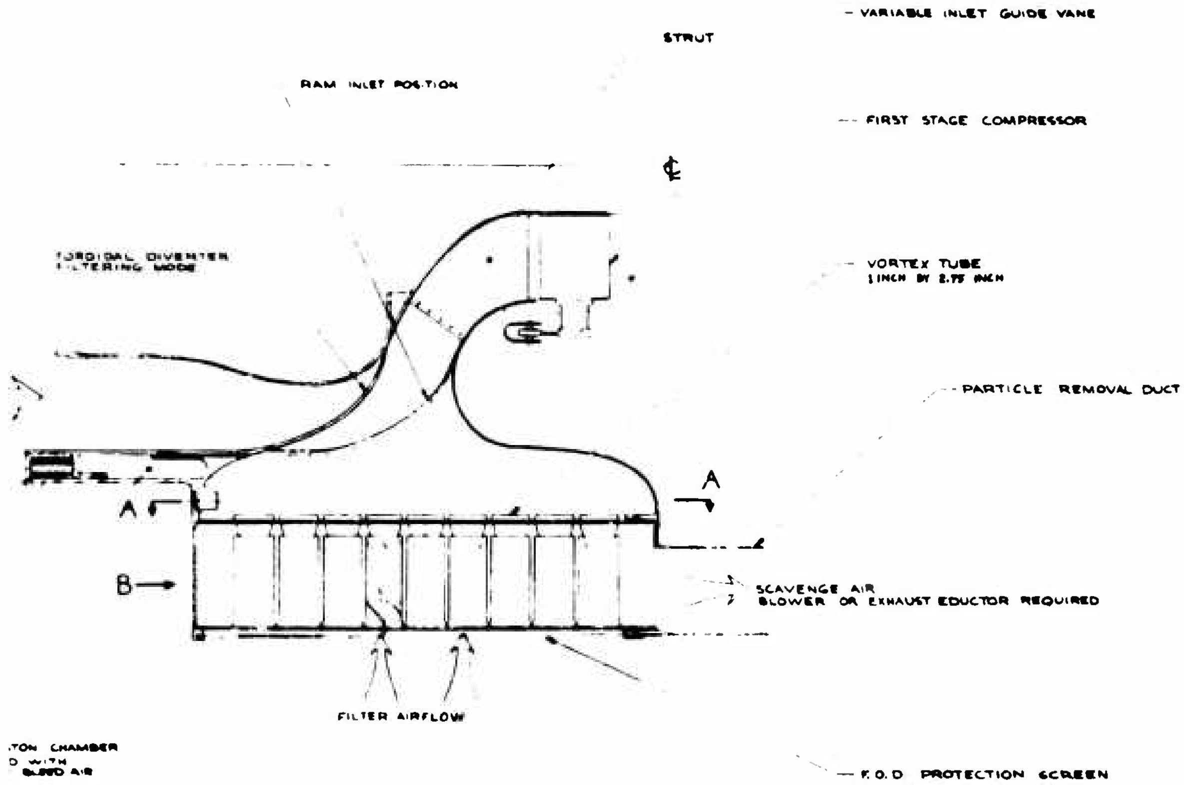



Figure 25. Integral Vortex-Tube Separator Conceptual Design.


VARIABLE INLET GUIDE VANE
STRUT
RAM INLET POSITION
FIRST STAGE COMPRESSOR
VORTEX TUBE
1 INCH BY 2.75 INCH
PARTICLE REMOVAL DUCT
A
A
B
SCAVENGE AIR
BLOWER OR EXHAUST EDUCTOR REQUIRED
FILTER AIRFLOW
F.O.D PROTECTION SCREEN

12

A toroidal diverter is included as part of the concept and will allow the separator to be bypassed and provide ram-air pressure recovery and anti-icing capability should it be required. The toroidal diverter is actuated by an annular piston mechanism. Normally it would be spring loaded in the ram inlet position. High-pressure air from the compressor would be used to load the annular piston and change the position of the toroidal diverter when required. Actuation would not entail a performance loss because the actuation bleed flow is momentary.

## TASK 3 - SELECTION OF TWO CONCEPTS

In the previous task, eight concepts were determined to be feasible, and preliminary design study layout drawings were prepared for each. Under the "Selection" task, an analysis of the eight concepts was made to determine relative separation efficiency, operational capability in adverse environment, net effect on engine performance, maintainability, reliability, relative cost, additional weight, additional volume, localized concentration effect, and self-contained operation. The first eight factors were specified in the contract Statement of Work, and the other two were considered applicable additions. Weighting factors for rating the separator concepts were established by using a binary technique of forced decision that is described in Reference 10. Figure 26 shows how the rating factors were weighted using this technique. A summary of resultant rating factor weight values is listed in Table III.

TABLE III. RATING FACTOR WEIGHT VALUES

| No. | Factors | Weight |
|---|---|---|
| 1 | Separation Efficiency | 9 |
| 2 | Operation in Adverse Environment | 5 |
| 3 | Effect on Engine Performance | 7 |
| 4 | Maintainability | 1 |
| 5 | Reliability | 6 |
| 6 | Cost | 2 |
| 7 | Weight | 4 |
| 8 | Volume | 1 |
| 9 | Localized Concentration Effect | 8 |
| 10 | Self-Contained Operation | 2 |

Since the preliminary design study layout drawings of the various separators were conceptual in nature, as opposed to detail designs for a specific engine, a rigorous analysis of each concept was not possible. Instead, the concepts were evaluated with respect to each other for each of the above rating factors using the same binary technique of forced decision. The concept evaluation rankings were then multiplied by the weighting value for each rating factor to obtain a mathematical ranking of the eight separator concepts. The results are summarized in Table IV. Based on the ranking in Table IV, the first two concepts were selected for feasibility demonstration during the balance of the program.

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | N |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Separation Efficiency | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 9 |
| Effect on Engine Performance | 0 | | | | | | | | | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 7 |
| Operation in Adverse Environment | | 0 | | | | | | | | 0 | | | | | | | | 0 | 1 | 1 | 1 | 1 | 0 | 1 | | | | | | | | | | | | | | | | | | | | | | 5 |
| Reliability | | | 0 | | | | | | | | 0 | | | | | | | 1 | | | | | | | 1 | 1 | 1 | 1 | 0 | 1 | | | | | | | | | | | | | | | | 6 |
| Weight | | | | 0 | | | | | | | | 0 | | | | | | | 0 | | | | | | 0 | | | | | | 1 | 1 | 1 | 0 | 1 | | | | | | | | | | | 4 |
| Volume | | | | | 0 | | | | | | | | 0 | | | | | | | 0 | | | | | | 0 | | | | | 0 | | | | | 0 | 1 | 0 | 0 | | | | | | | 1 |
| Maintainability | | | | | | 0 | | | | | | | | 0 | | | | | | | 0 | | | | | | 0 | | | | | 0 | | | | 1 | | | | 0 | 0 | 0 | | | | 1 |
| Cost | | | | | | | 0 | | | | | | | | 0 | | | | | | | 0 | | | | | | 0 | | | | | 0 | | | | 0 | | | 1 | | | 0 | 1 | | 2 |
| Localized Concentration Effect | | | | | | | | 0 | | | | | | | | 1 | | | | | | | 1 | | | | | | 1 | | | | | 1 | | | | 1 | | | 1 | | 1 | | 1 | 8 |
| Self-Contained Operation | | | | | | | | | 0 | | | | | | | | 0 | | | | | | | 0 | | | | | | 0 | | | | | 0 | | | | 1 | | | 1 | | 0 | 0 | 2 |

Figure 26. Rating Factor Weighting Technique.

| TABLE IV. SEPARATOR CONCEPT SELECTION SUMMARY | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Rating Factor | $\eta_{Separation}$ | Operation in Adverse Environment | Effect on Engine Performance | Maintainability | Reliability | Cost | Weight | Volume | Localized Concentration | Self-Continued Operation | Total |
| Semi-Reverse Flow | 45 | 35 | 42 | 7 | 42 | 10 | 20 | 5 | 40 | 14 | 260 |
| Powered Mixed Flow | 54 | 35 | 42 | 4 | 18 | 14 | 24 | 6 | 32 | 14 | 243 |
| Diffuser Interstage | 45 | 35 | 49 | 3 | 12 | 14 | 28 | 7 | 32 | 10 | 235 |
| Inlet Inertial | 18 | 35 | 28 | 6 | 36 | 8 | 16 | 4 | 32 | 4 | 187 |
| Vortex Tubes | 54 | 10 | 7 | 5 | 36 | 0 | 8 | 1 | 56 | 4 | 181 |
| Self-Cleaning Barrier | 63 | 5 | 7 | 0 | 18 | 2 | 8 | 2 | 56 | 4 | 165 |
| Rotating Filament | 9 | 35 | 28 | 1 | 0 | 4 | 16 | 4 | 0 | 10 | 107 |
| Electrostatic Diversion | 0 | 20 | 21 | 2 | 12 | 6 | 8 | 0 | 24 | 6 | 79 |

## TASK 4 - TEST HARDWARE DESIGN

In this task, test hardware was designed to experimentally evaluate the semi-reverse-flow and powered mixed-flow particle separator concepts that had been selected and approved for feasibility demonstration in the previous task. The two concepts were refined, and manufacturing layout drawings were prepared of analytically optimized non-flight-weight test rigs designed to flow 8.0 lb/sec of clean air. The rig designed to test the semi-reverse-flow separator concept is entirely new. The rig designed to test the powered mixed-flow separator concept is an adaptation of a rig previously used for conducting a 10-hour sand-ingestion test with single-stage impeller.

### SEMI-REVERSE-FLOW SEPARATOR MECHANICAL DESCRIPTION

Test hardware was designed to demonstrate the feasibility of the semi-reverse-flow particle separator concept. The hardware as shown in Figure 27 is basically composed of three sections constructed of aluminum. The first section is a flow measurement adapter that connects the rig to the facility dust feeder screen basket assembly. The second section is the semi-reverse-flow concept test item designed so that it can be tested with and without swirl vanes. The third section is an adapter that simulates a compressor inlet sized to flow 8.0 lb/sec and also incorporates a particle scavenge duct sized to flow 3.2 lb/sec. Airflow conditions will be monitored in this section with a traversing cobra probe to obtain total pressure and swirl angle measurements.

### SEMI-REVERSE-FLOW SEPARATOR DESIGN CONSIDERATIONS

The test section was analytically optimized to provide maximum particle separation with respect to pressure loss. Design criteria, supplied by United Aircraft of Canada, Ltd., based on their Bell Model 212 inertial separator intake, were utilized in arriving at the geometric contour and flow splitter position. The rectangular UACL inlet is sized for approximately 8.0 lb/sec flow rate. The duct areas were scaled up to accommodate the 11.2 lb/sec flow rate required by the semi-reverse-flow concept, and at the same time were converted into an annular form. UACL has experimented with reducing turning losses in the inlet and has developed the contour for a Coanda ramp that not only helps turn the flow, but at the same time increases separation efficiency. Dimensions for the Coanda ramp were scaled directly from the UACL design based on the annular height of the duct at that point. The placement of the flow splitter was based on maintaining UACL's recommended ratio of 0.333 for the height of the Coanda ramp above the flow splitter, to the distance from the Coanda ramp to the flow splitter leading edge. The UACL separator discharges into a plenum chamber surrounding the engine, where the flow is decelerated and then accelerated again as it enters the engine. To minimize pressure losses in the semi-reverse-flow separator, the plenum chamber has been replaced with an annular duct that would be an integral part of the engine inlet.

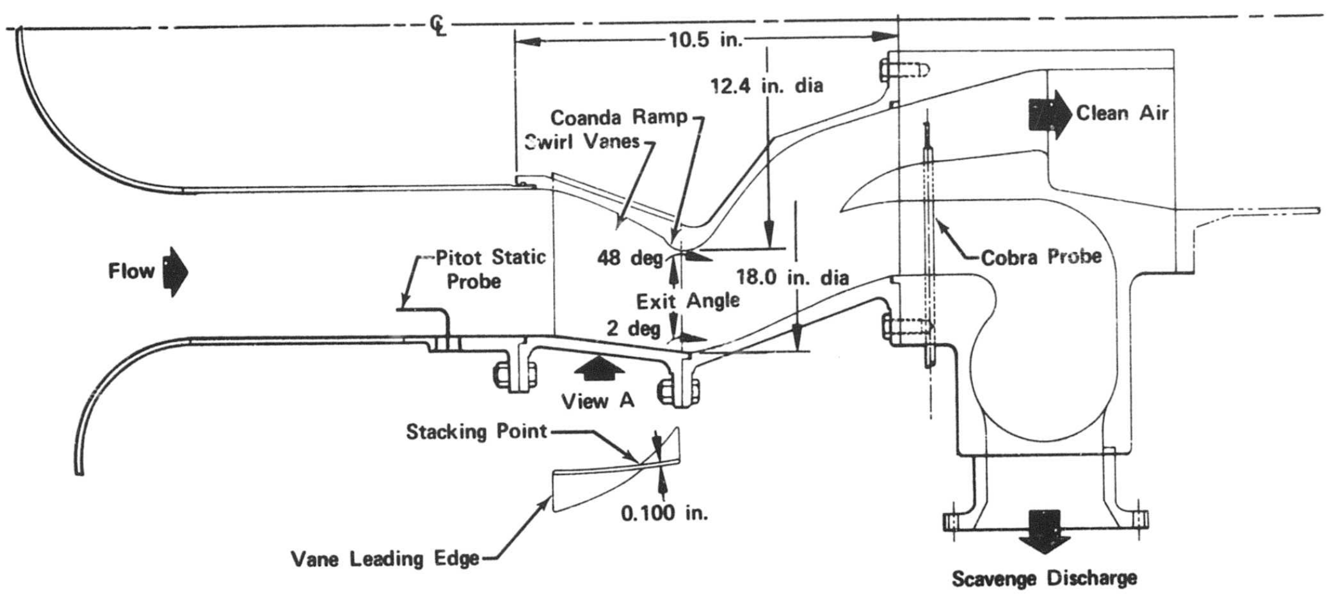



Figure 27. Semi-Reverse-Flow Particle Separator Test Rig.

After defining the gas flow path, it was then analyzed at FRDC to determine pressure loss as a function of mean inlet swirl vane angle. The results shown in Figure 28 indicate that the slope of the pressure loss vs mean swirl angle curve begins to increase at about 30 deg mean swirl angle and 6 inches $H_2O$ pressure drop. As a result, a mean swirl angle of 30 deg was selected. A graphics display computer program was then utilized to generate optimized camber distributions which resulted in twisted swirl vanes having approximately 48 deg swirl angle at the hub and 2 deg at the tip. A plot of swirl-vane exit angle as a function of span is shown in Figure 29. Twisting the swirl vanes in this manner will impart maximum swirl to the particles in the vicinity of the hub where it is needed most. A total of 18 swirl vanes are cantilevered from the hub and stacked about the chord midpoint. For ease of fabrication, instead of having an airfoil shape, the swirl vanes will be made from 0.100-in.-thick sheet aluminum.

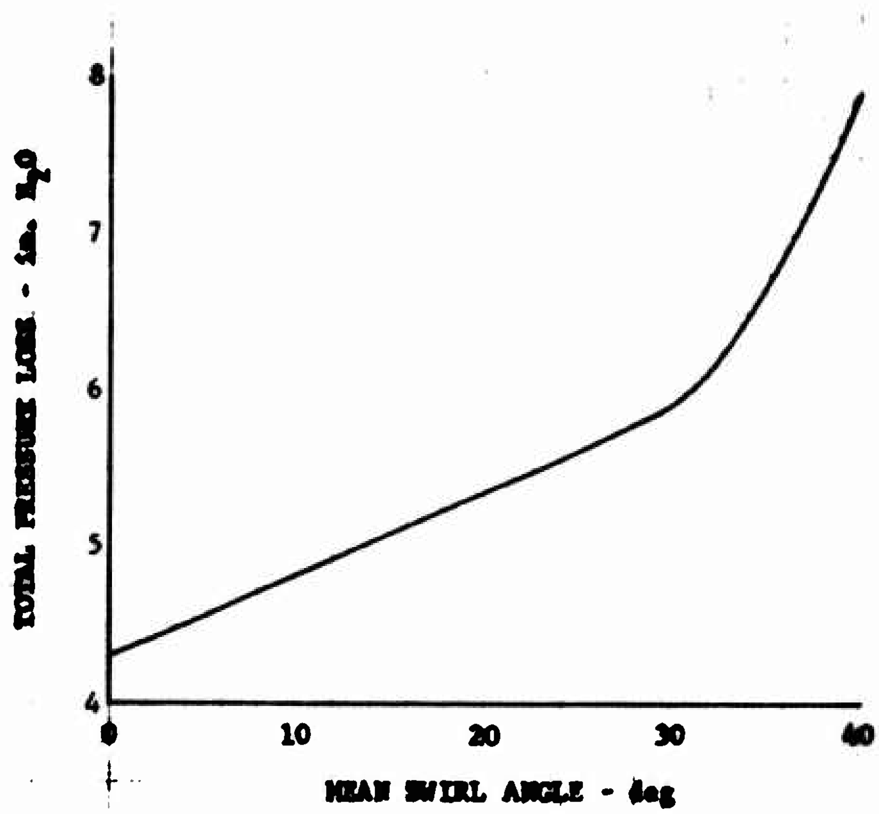



Figure 28. Estimated Total Pressure Loss.

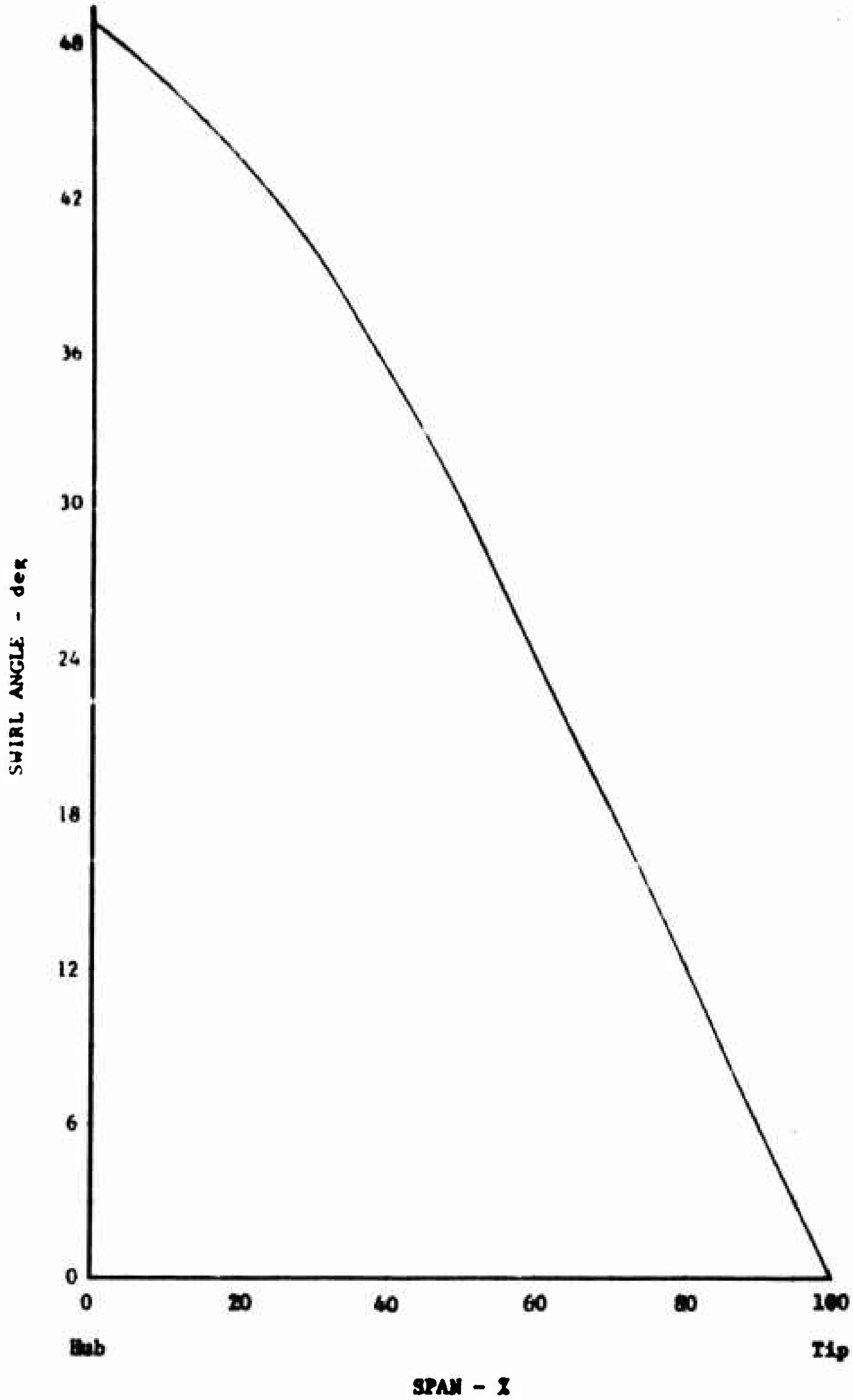



Figure 29. Swirl-Vane Trailing-Edge Exit Angle Geometry.

The particle trajectory computer program was used to analyze particle behavior in the semi-reverse-flow separator with an average gas swirl of 30 deg. The results, shown in Figure 30, indicate that only very small particles entering the separator near the hub will escape separation. To evaluate analytically the effect of operating the semi-reverse-flow separator without swirl vanes, another computer run was made without inputting any gas swirl. The results, shown in Figure 31, indicate a reduced concentration of particles at the OD, as would be expected, and an increase in fine particles that were not separated.

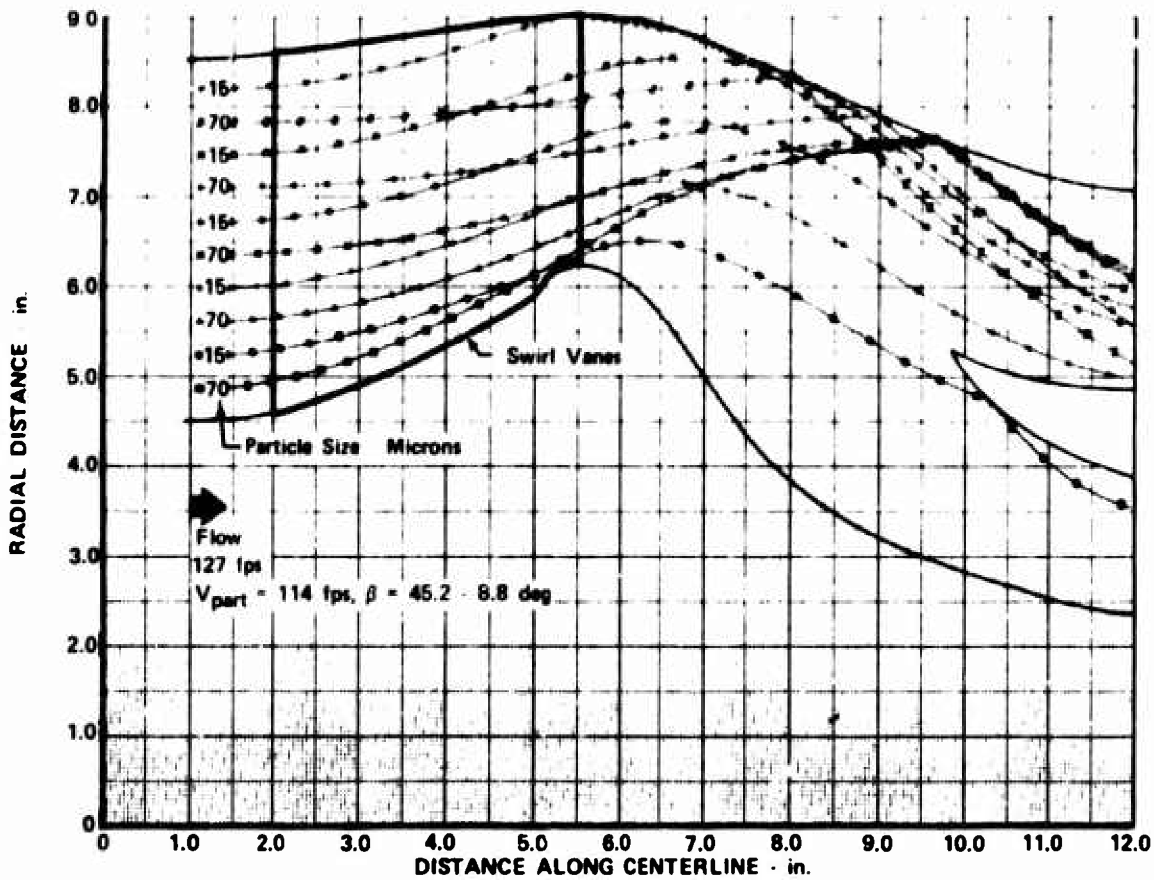



Figure 30. Calculated Particle Trajectories in Semi-Reverse-Flow Separator With Simulated 30-Degree Gas Swirl.

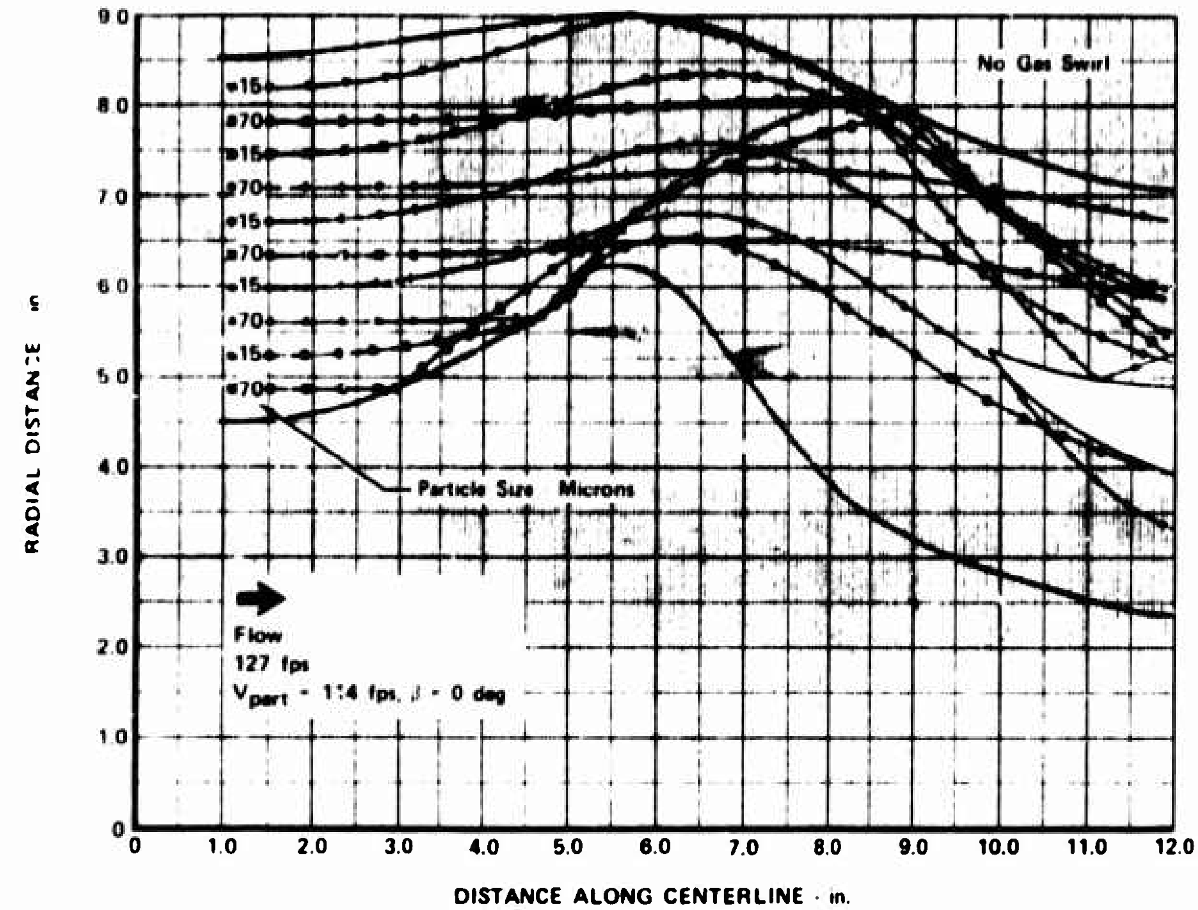



Figure 31. Calculated Particle Trajectories in Semi-Reverse-Flow Separator With No Gas Swirl.

POWERED MIXED-FLOW SEPARATOR MECHANICAL DESCRIPTION

Test hardware was designed to demonstrate the feasibility of the powered mixed-flow separator concept. The test hardware, shown in Figure 32, is basically an adaption of an existing rig that was used for conducting sand-ingestion tests. The bellmouth rig inlet connects the rig to the test facility dust feeder screen basket assembly. The inlet assembly consists of a flow measurement section, a simulated bearing housing with four struts, and variable inlet guide vane assembly. The rig has a special bearing system with an oil-damped bearing support and a seal package designed to keep dust out of the bearings. Recommended axial thrust loads are maintained by pressurizing a thrust balance piston within the bearing housing. The mixed-flow impeller is an existing impeller that was modified by cutting off a portion . The shroud section is designed as a split assembly so that it can be tested with the constant area contour and then readily removed for final machining of the particle scavenge zone. Separate annular collection chambers are provided for segregating the scavenge discharge and clean airflow. Impelier discharge flow conditions will be monitored

downstream of the scavenge zone splitter with a traversing Cobra probe to obtain total pressure, total temperature, and swirl angle measurements.

## POWERED MIXED-FLOW SEPARATOR DESIGN CONSIDERATIONS

A majority of the analytical design effort was associated with evaluating the mixed-flow impeller configuration and shroud contour. Because of the time and cost that would be involved in designing and fabricating a new impeller, the feasibility of modifying an existing impeller was studied. This analysis determined that by utilizing the axial flow inducer section and a portion of the centrifugal flow section, a reasonable mixed-flow impeller could be created. A meridional view of the impeller showing the recommended cutoff point is presented in Figure 33. The resultant calculated pressure rise across the span at an estimated efficiency of 82 percent is shown in Figure 34. It is estimated that the overall stage pressure ratio will average out to be approximately 1.7 to 1. To reduce tip loading, which was considered to be somewhat high, and to minimize potential stability problems, the blade tip will be uncambered 15 degrees with a linear variation to 0 degrees uncamber at the root.

The impeller that will actually be modified is one that has previously been used in a 10-hour sand ingestion test. As shown in Figure 35, the most severe erosion that resulted from this test occurred at a region on the OD of the full-blade pressure surface that is downstream of where the impeller will be cut off. Thus, blade erosion should not be a problem for the impeller when it is reworked to a mixed-flow configuration.

Because inlet conditions that might be required for a second-stage compressor were not defined, the initial duct contour downstream of the impeller was designed for constant area. The particle trajectory computer program was then utilized to evaluate particle behavior in this duct. For the particle trajectory plot shown in Figure 36, an average gas swirl of 60 degrees was used to simulate the impeller. This centrifuged the particles to the OD but did not account for the effect of particles that might be impacted by the impeller blades. However, good correlation was obtained between an indicated concentration of particles at the shroud OD and at the point where maximum erosion occurred on the impeller during the sand ingestion tests. An effort was made to simulate the effect of particle impaction by first calculating estimated particle rebound velocities and angles off the impeller blade and then using this as input to the particle trajectory computer program. The results presented in Figure 37 show that the particles tend to become focused near the maximum OD of the shroud.

Having established potential particle trajectories, the computer program was then used to evaluate shroud contour changes that would result in particle capture. Figure 38 shows a plot of particle trajectories with the shroud contour changed to enhance particle capture. The results indicate that even fine particles which started near the hub would be captured by the predicted scavenge zone. Increasing the shroud diameter in the vicinity of the impeller produced superior particle concentration in the predicted scavenge zone, as shown in Figure 39. The predicted scavenge zone is located so that it should also capture particles that might be impacted by the impeller. To substantiate the particle trajectory computer program predictions, initially the constant-area shroud contour will be tested briefly with paint on the internal surfaces to verify the location of particle scavenge zone prior to final machining.

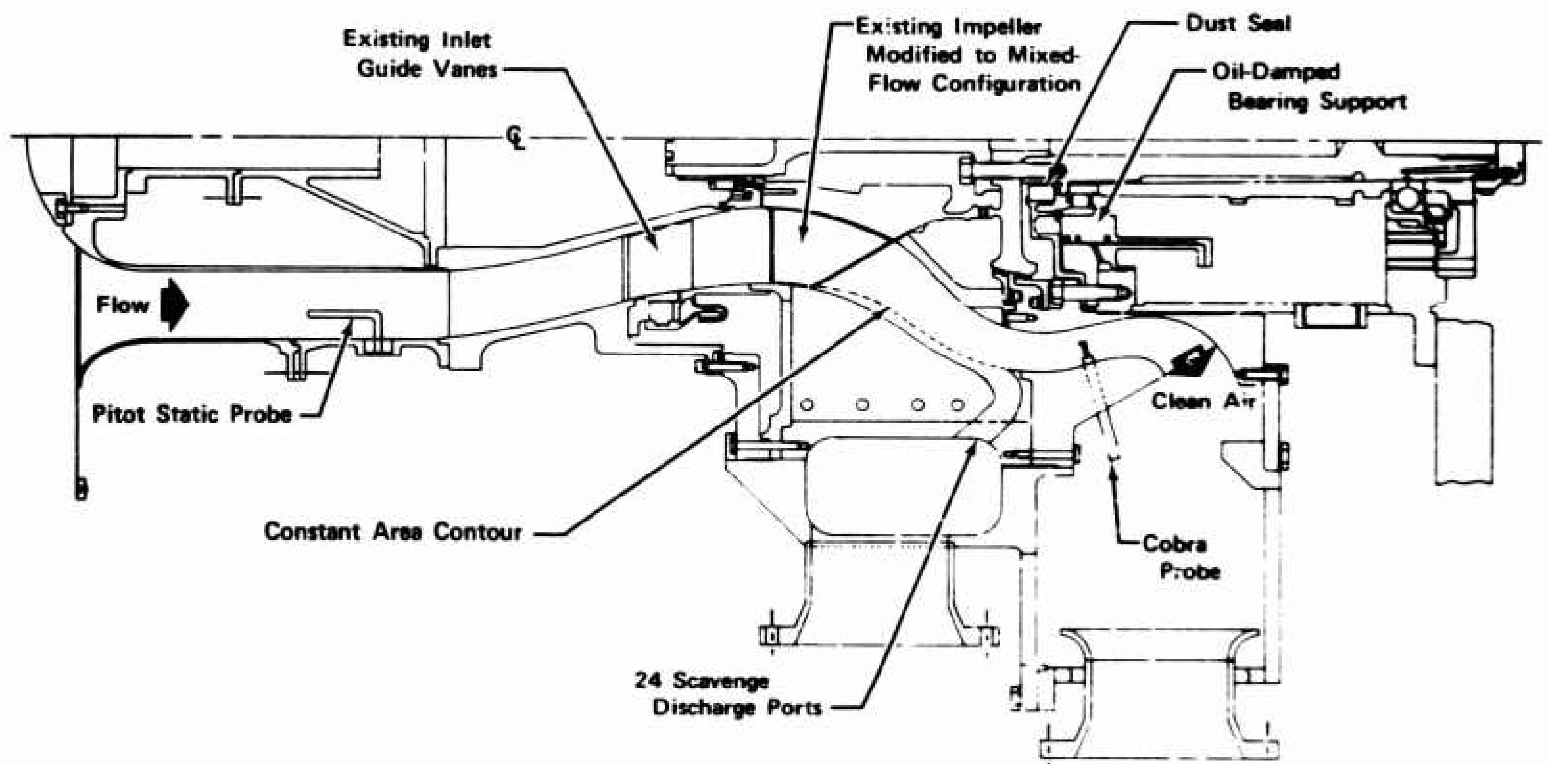



Figure 32. Powered Mixed-Flow Particle Separator Test Rig.

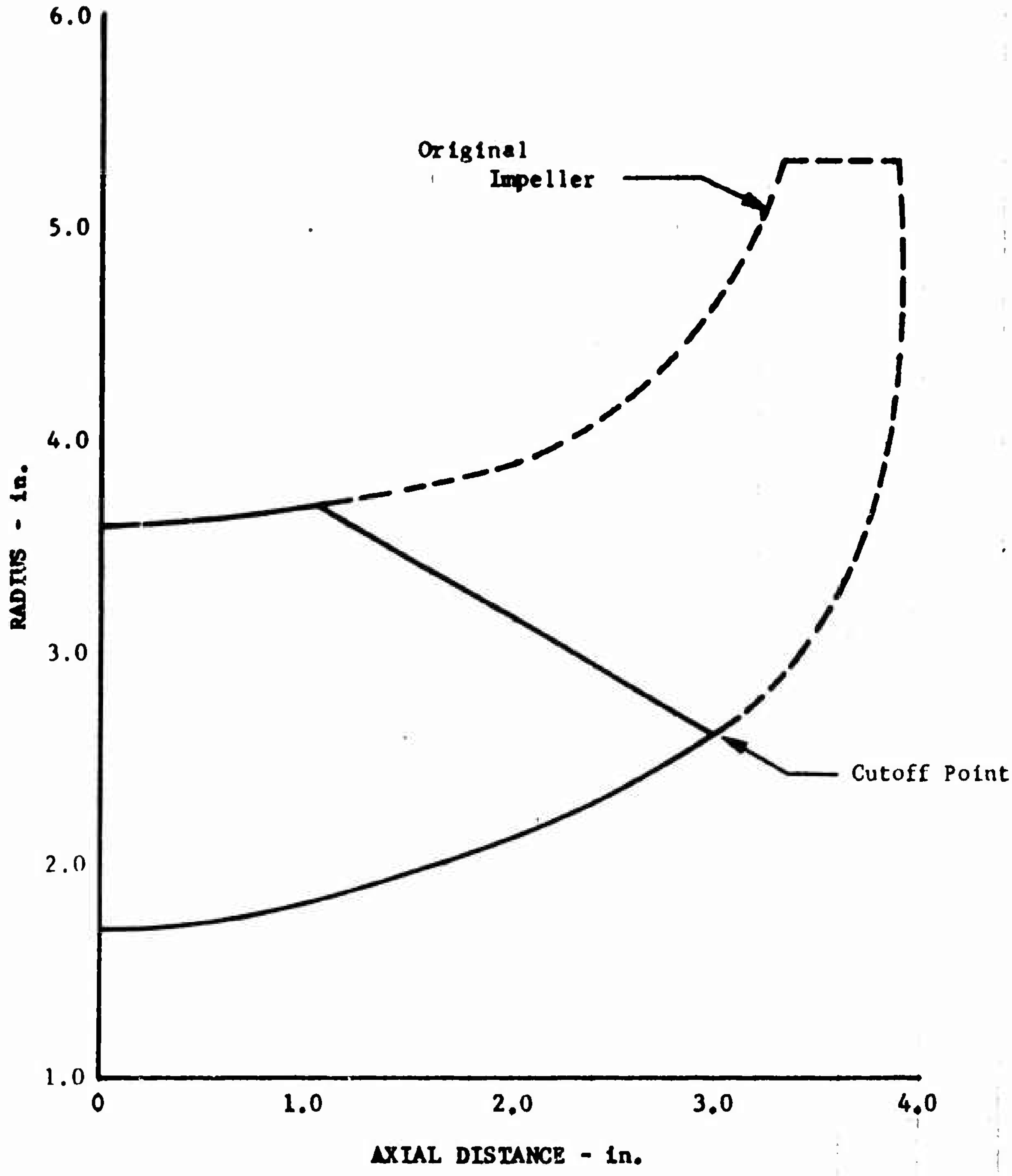



Figure 33. Meridional View of Impeller Modification.

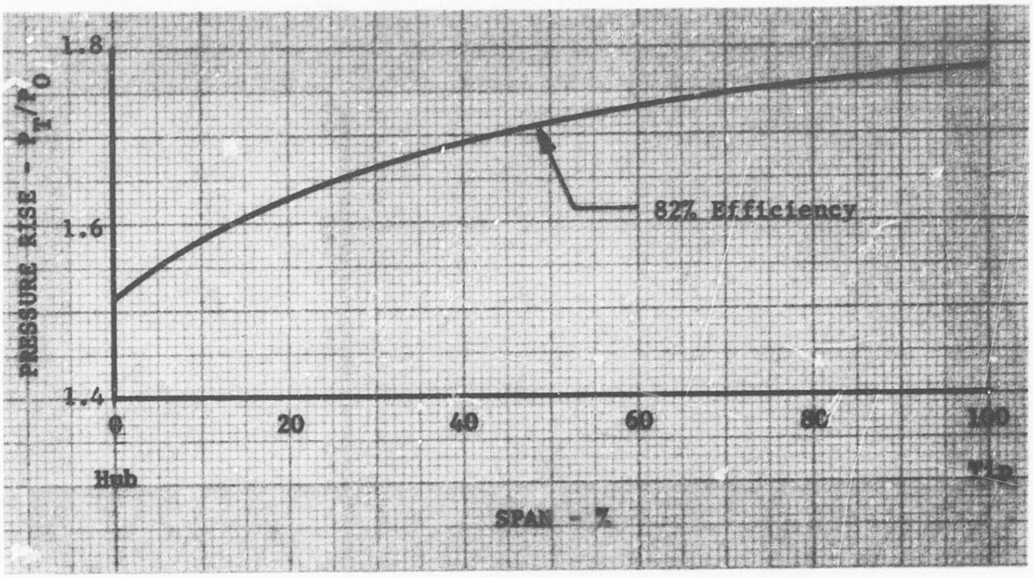



Figure 34. Estimated Pressure Rise Across Impeller Span.

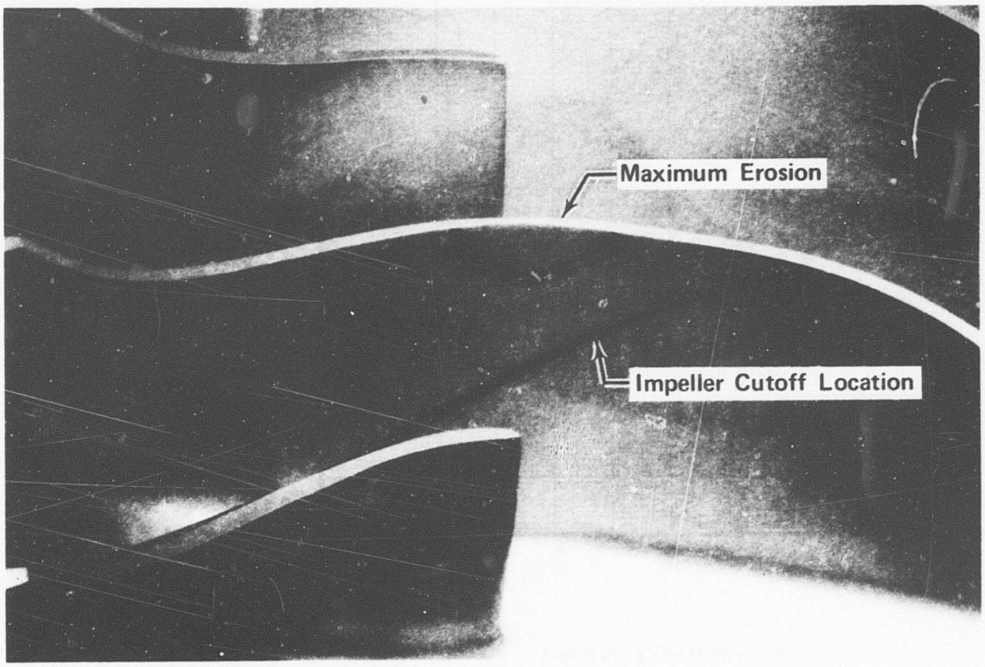



Figure 35. Location of Impeller Cutoff Upstream of Maximum Erosion Region.

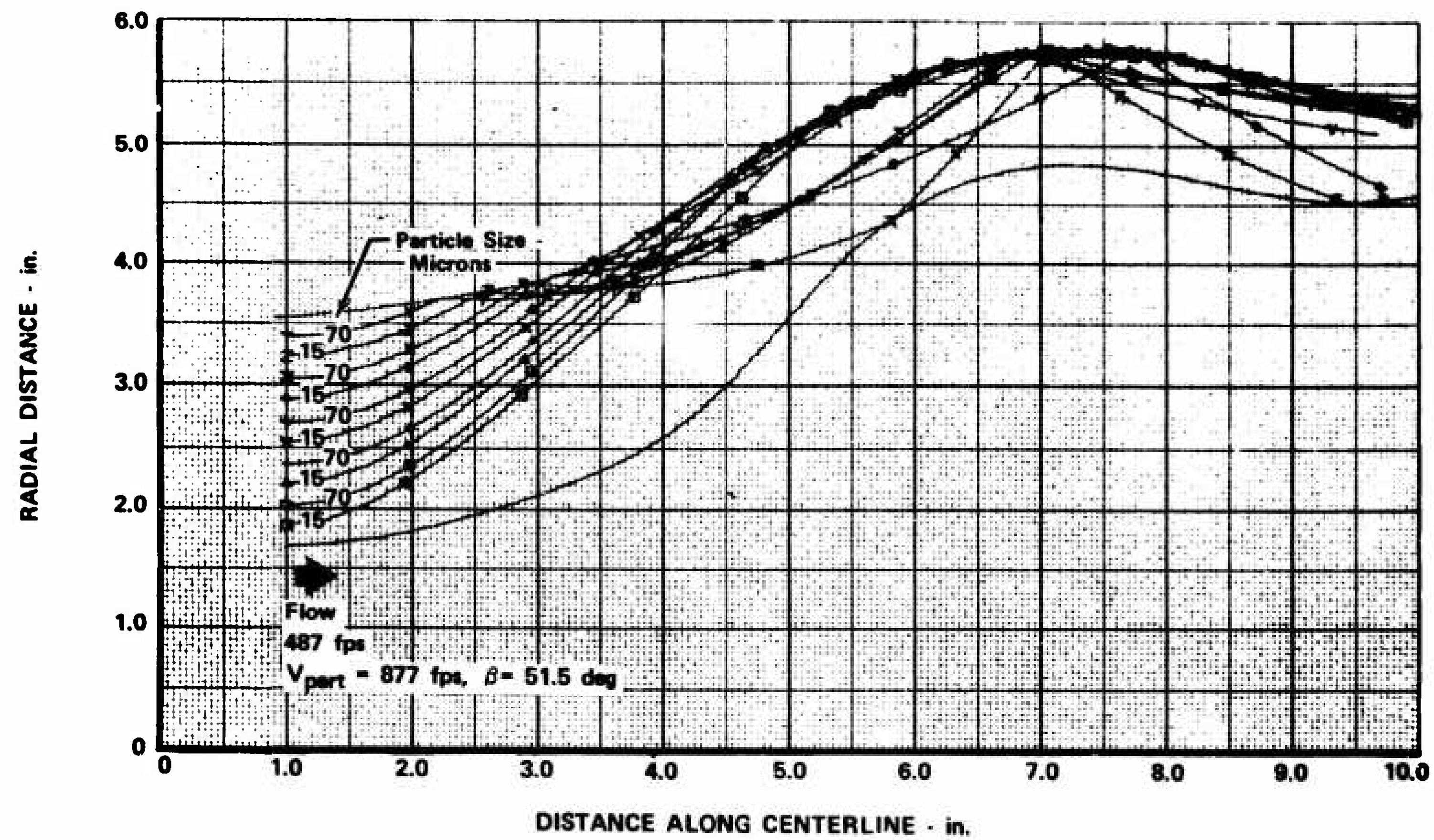



Figure 36. Calculated Centrifugal Effect on Particle Trajectories in Powered Mixed-Flow Separator With Simulated 60-Degree Gas Swirl.

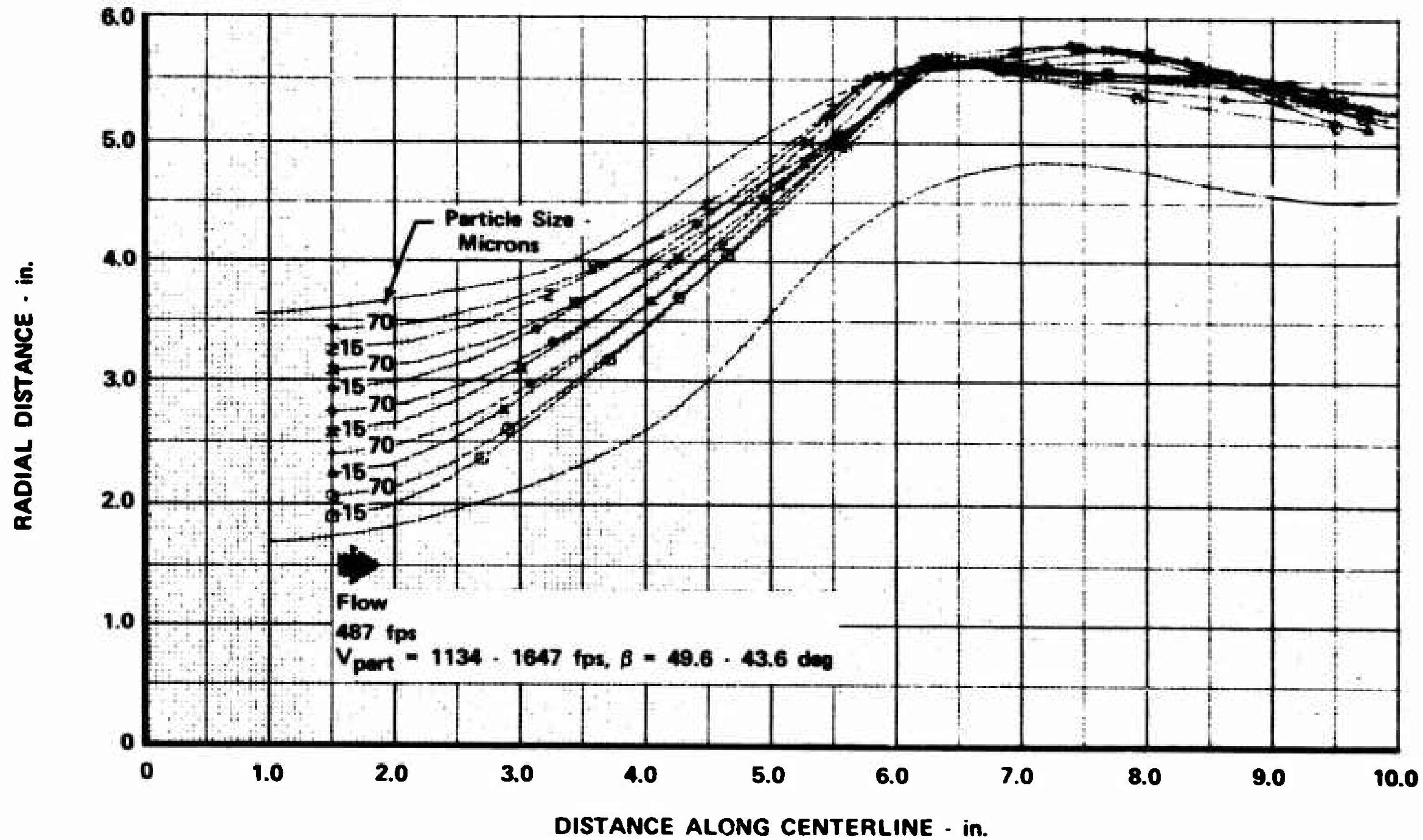



Figure 37. Calculated Impaction Effect on Particle Trajectories in Powered Mixed-Flow Separator With Simulated 60-Degree Gas Swirl.

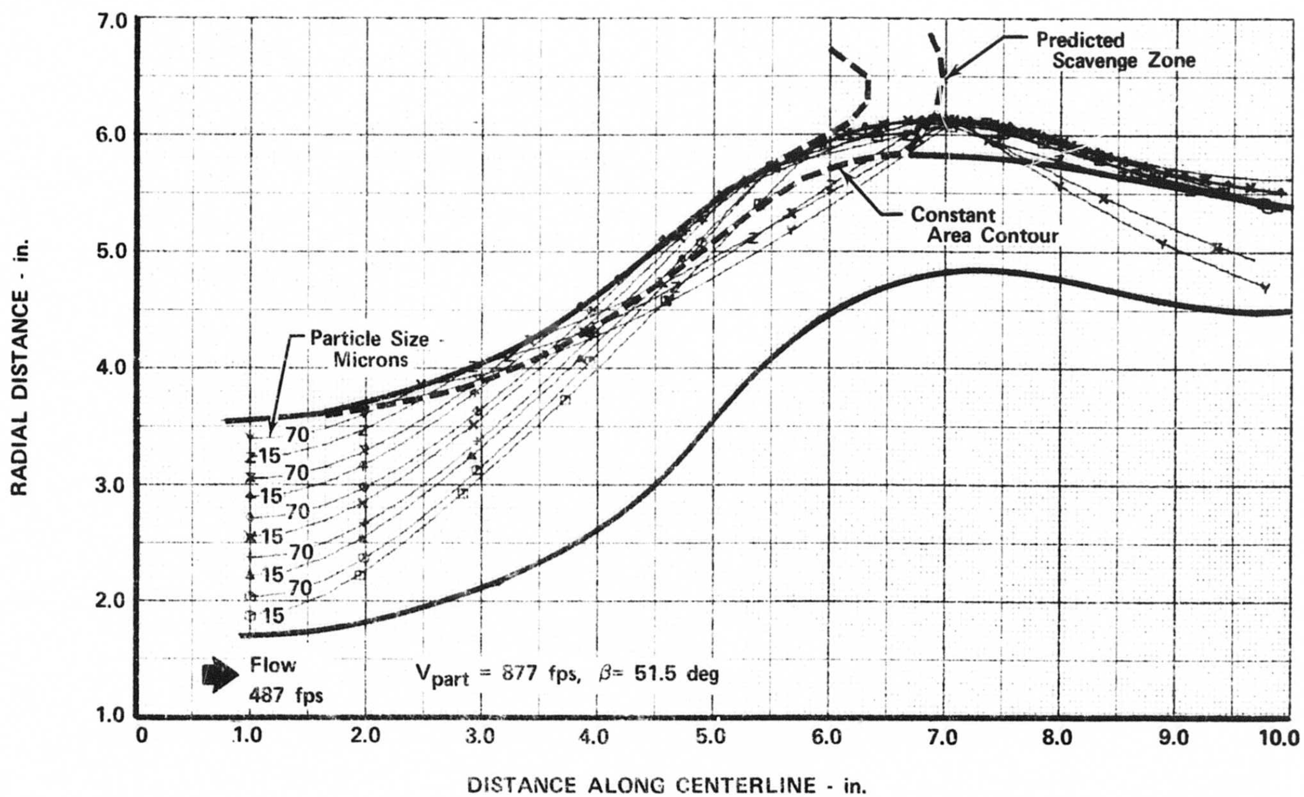



Figure 38. Particle Capture in Predicted Scavenge Zone Resulting From Shroud Contour Change.

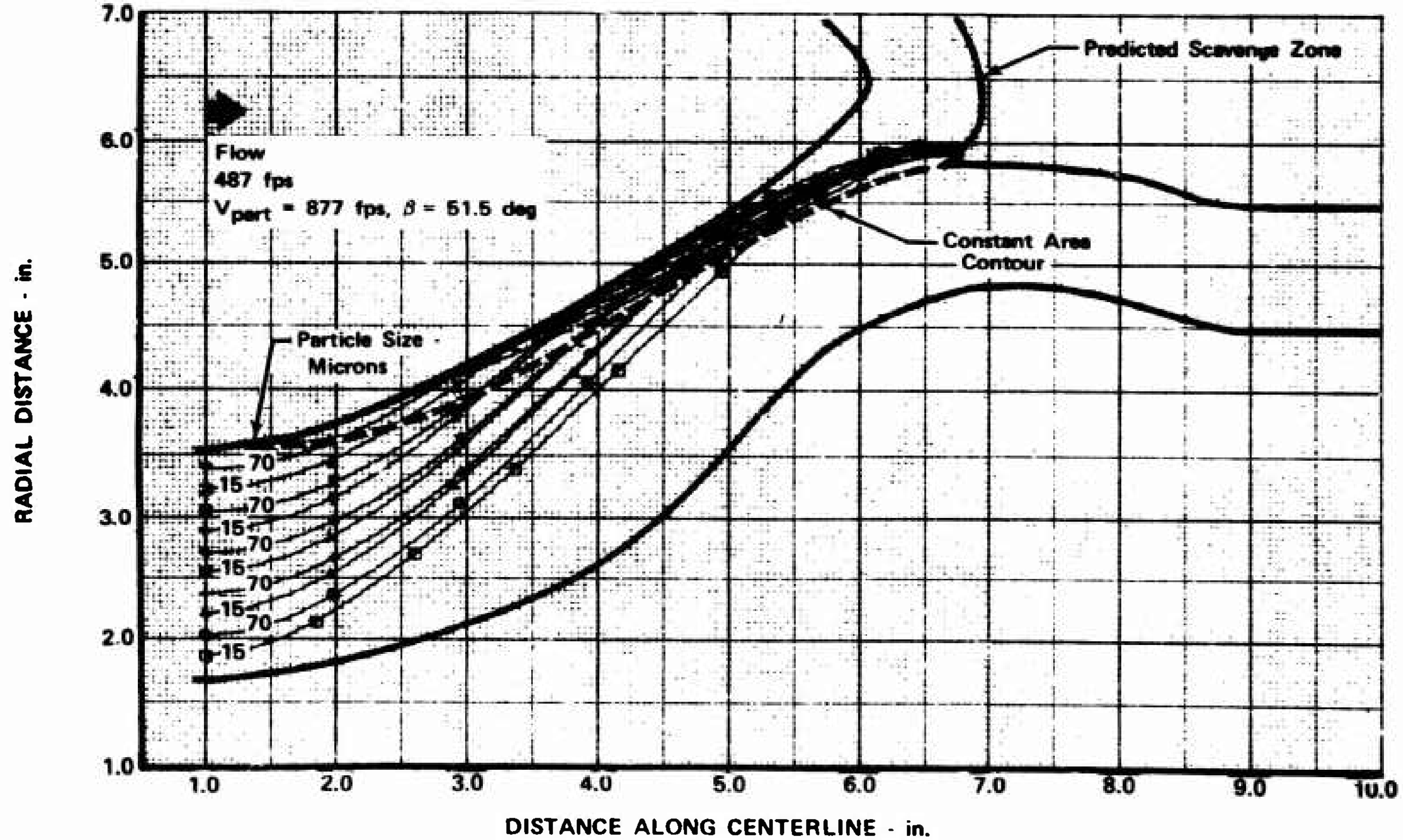



Figure 39. Superior Particle Concentration in Scavenge Zone Produced by Increased Shroud Diameter in Vicinity of Impeller.

## CONCLUSION

It is concluded that of the integral engine inlet particle separator concepts investigated, the semi-reverse-flow and powered mixed-flow concepts are feasible and are the most promising concepts when evaluated on the basis of the stated criteria.

## LITERATURE CITED


1. Elsasser, T. E., NAPTC'S COMMON DENOMINATOR IN ADVANCING THE STATE-OF-THE-ART OF INLET PARTICLE SEPARATORS, Naval Air Propulsion Test Center, 9th National Conference on Environmental Effects on Aircraft and Propulsion Systems, October 1969.

2. Poplawski, R., and R. A. Miller, MICROSCOPIC PARTICLE SEPARATION AND APPLICATIONS, Aerospace Research Laboratories, Wright-Patterson Air Force Base, February 1968.

3. Lea, A. J., PARTICLE SEPARATOR EFFICIENCY EVALUATION AND DEVELOPMENT PROGRAM FOR U21A AIRCRAFT, United Aircraft of Canada Ltd., Contract DAAJ01-67-C-2257(G) Phase I Final Report, USAVCOM, April 1968.

4. Connors, H. D., DEVELOPMENT OF THE LYCOMING INERTIAL PARTICLE SEPARATOR, AVCO Lycoming Division, 7th National Conference on Environmental Effects on Aircraft and Propulsion Systems, September 1967.

5. Hogg, G. J., and E. H. Standt, DEVELOPMENT OF THE BOEING INERTIAL SEPARATOR FOR THE CH-46 HELICOPTER, The Boeing Company, Vertol Division, 9th National Conference on Environmental Effects on Aircraft and Propulsion Systems, October 1969.

6. Shalman, Yu. I., WEAR AND PERFORMANCE VARIATION OF AXIAL AND CENTRIFUGAL COMPRESSOR STAGES OPERATING IN DUSTY AIR, Vertoletyye Gazoturbinnyye Dvigateli, Moscow, 1966.

7. Meriwether, R. F., DEVELOPMENT OF A PROTOTYPE SELF-CLEANING FILTER FOR THE PERSHING MISSILE POWER STATION GAS TURBINE, Southwest Research Institute Report No. 557, Army Engineer Research and Development Labs, Ft. Belvoir, Va., Contract DA-44-009-Eng-5245, December 1964, AD-460 620L.

8. INVESTIGATION OF THE FEASIBILITY OF INTEGRAL GAS TURBINE ENGINE SOLID PARTICLE INLET SEPARATORS, Technical Proposal, PWA FP 69-55, 11 August 1969.

9. CONDUCT LABORATORY MODEL FEASIBILITY STUDY AND FURNISH ROTATING BRUSH SEPARATOR, IITRI Report No. 66154-8, Naval Air Systems Command, Washington, D. C., Contract N00019-68-C-0459, March 1969, AD-850 706.

10. Fasal, John, FORCED DECISIONS FOR VALUE, Product Engineering, 12 April 1965.

11. Wilson, M. P., Jr., and W. P. Goss, PARTICLE DYNAMICS IN VARIOUS FLOW FIELDS, Pratt & Whitney Aircraft, East Hartford Report APM 1193, 17 June 1969.

## APPENDIX
## DESCRIPTION OF PARTICLE TRAJECTORY COMPUTER PROGRAM

### DUCT FLOW FIELD CALCULATIONS

The theoretical analysis of incompressible turbulent swirling flow through axisymmetric annular ducts is obtained using standard numerical techniques to obtain solutions to the governing partial differential equations of motion. To account for the effect of boundary-layer growth on the pressure field in the duct, the equations of motion are derived in a streamline coordinate system which closely approximates the streamlines of the real flow. The most suitable orthogonal coordinate system for this purpose is that obtained from the potential flow solution, in which the stream function forms the normal coordinate and the velocity potential forms the streamwise coordinate. The elliptic properties of the flow are then reflected in the coordinate system. Since the coordinates serve as a first approximation to the flow, the equations of motion are then simplified by assuming that the velocity normal to the potential-flow streamlines is small compared to the streamwise velocity ($u_n << u_s$). The turbulent flow in the duct is then treated as a single flow regime governed by a parabolic partial differential equation. The difficult problem of matching the boundary-layer solution (parabolic equation) to the potential flow (elliptic equation) is avoided and the complete solution is obtained without an iterative procedure. Thus the streamwise and normal static pressures are obtained as a solution of the parabolic boundary-layer-type equations, with the boundary condition that mass flow is preserved.

The turbulence in the boundary-layer flow is represented by the mixing length theories of von Karmen and Prandtl, which relate the eddy viscosity to the local mean flow properties. These theories use a damping factor derived by Van Driest for the flow near the wall and the wake model of Clauser for the outer layer. The computing program is devised such that should flow separation occur at any region in the duct, further computations of the flow properties will cease. With this aid, duct contours have been optimized so as to minimize flow separation.

Since the equations of motion are of the boundary-layer type and are parabolic, the flow is completely specified by the initial conditions and boundary conditions. The initial conditions require that the velocity distribution of the flow entering the duct be specified; the boundary conditions specify the no-slip condition at the walls. The solution is then determined to within one arbitrary constant P, the reference static pressure. Thus, once a problem has been solved in a given coordinate system, the relationship between the downstream and upstream conditions is fixed. The explicit numerical method used to solve the governing equations is a modified form of the Runge-Kutta integration formula.

## PARTICLE TRAJECTORY CALCULATIONS

The flow field determined for the duct is used by the particle trajectory analysis program, which computes and plots the trajectories of particles as they pass through the duct. The flow properties must be input at discrete points throughout the duct by defining the coordinates of the point, the magnitude of the gas velocity vector in the meridional plane and perpendicular to the meridional plane, the angle it makes with the axis of symmetry, and the gas total pressure and total temperature. In the calculations, flow properties are interpolated linearly between the four points that surround the particle.

Particles may be input at any location in the duct and must have specified properties. Particles are considered spherical for purposes of mass, area and drag calculations. Total relative velocity is calculated based on the particle and local gas velocities:

$$V_{rel} = \sqrt{(V_{gx} - V_{px})^2 + (V_{gy} - V_{py})^2 + (V_{gz} - V_{pz})^2}$$

The Reynolds number of a particle is calculated by:

$$Rey = \frac{\rho_{gas} V_{rel} d}{\mu}$$

where d is the particle diameter.

Particle drag coefficient is obtained from a polynomial relationship of $C_D$ and Rey obtained from published curve-fitted experimental data (Reference 11). As a particle moves through the duct, drag forces are calculated based on total relative particle velocity:

$$F_{drag} = 1/2 \; \rho_{gas} V2_{rel} \; AC_D$$

where 'A' is the projected frontal area of a sphere. Since the particle mass is known from its density, the particle acceleration is expressed by:

$$a = \frac{3}{4} \frac{C_D \; \rho_{gas} \; V2_{rel}}{\rho_{part} \; d}$$

Assuming that drag force is the only force acting on a particle (gravitational forces are negligible compared to aerodynamic forces), this relation can be used to compute the three components of particle acceleration. These accelerations are considered constant over small time intervals and are integrated directly to give the change in particle velocity and position for that interval. In the event that a particle strikes a

wall, it is rebounded according to the particle's coefficient of restition.

A program option is available which determines the effects of the presence of an electrostatic field on the particle trajectories. An initial electrostatic charge is applied to the particles and a field strength is specified at any region of the duct. Electrostatic forces are calculated according to

$$F_{elec} = - EQ$$

where E is the field strength and Q is the particle charge. Thus, changes in particle acceleration due to electrostatic as well as aerodynamic forces may be calculated.

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13. ABSTRACT

Helicopter operations from unimproved landing sites have demonstrated the vulnerability of unprotected gas turbine engines to sand and dust ingestion. As an interim solution, engine inlet filtration or particle separator devices have been added to engines and aircraft that were already designed and developed. However, there is a need for particle separators designed to be integral with the engine from its conception to minimize penalties in engine performance, weight, maintainability, and reliability. The objective of this program is to conduct a two-phase investigation of particle separators intended to be an integral part of future advanced-technology gas turbine engines. Phase I involves feasibility study and design; Phase II involves feasibility demonstration. The effort reported herein describes the work accomplished during the first phase. Eight particle separator concepts were determined to be feasible, and preliminary design study layout drawings were prepared for each. Design information for three of the concepts was obtained from organizations that have been active in the field of particle separation; a review of current separator designs led to the development of a new concept; and the rest were formulated by Pratt & Whitney Aircraft. The eight separator concepts were evaluated with respect to each other for each of ten rating factors. The two most promising concepts, "semi-reverse flow" and "powered mixed-flow," were selected for feasibility demonstration. Test hardware was then designed to experimentally evaluate the two selected concepts.

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| Integral Engine Inlet Separators | | | | | | |
| Mixed Flow Compressor | | | | | | |

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